8 November 1991

FINAL REPORT

AND

GPS SYSTEM SPECIFICATION FOR SHIPBOARD TACAN REPLACEMENT

CDRL A003

GPS System Specification for Shipboard TACAN Replacement

Contract No. N62269-91-C-0008

Submitted to

Naval Air Development Center Code 4013
Warminster, PA 18974-5000

By

AJ Systems
1131 Seena Avenue
Los Altos, CA 94024

Contract Dollar Amount: $51,231.00
Contract Award: Competitive
Contract Sponsor: Peter Paul Fischer, Code 4013

8 November 1991

FINAL REPORT

AND

GPS SYSTEM SPECIFICATION FOR SHIPBOARD TACAN REPLACEMENT

CDRL A003

GPS System Specification for Shipboard TACAN Replacement

Contract No. N62269-91-C-0008

Submitted to

Naval Air Development Center Code 4013
Warminster, PA 18974-5000

By

AJ Systems
1131 Seena Avenue
Los Altos, CA 94024

3

THIS PAGE INTENTIONAL LEFT BLANK

TABLE OF CONTENTS

5

TABLE OF CONTENTS, CONTINUED

6

TABLE OF CONTENTS, CONTINUED

LIST OF FIGURES

8

LIST OF TABLES

9

LIST OF APPENDICES

/0

1.0 INTRODUCTION

This final report is the submission of Contract Data Requirements List (CDRL) A003 for Contract No. N62269-91-C-0008, GPS System Specification for Shipboard TACAN Replacement. This final report includes the GPS System Specification for Shipboard TACAN Replacement. This final report covers Tasks 1 through 12 of the contract, which are as follows:

1) Review Shipboard TACAN requirements,

2) Investigate existing data links,

3) Derive Differential (DGPS) technique and associated data link content,

4) Derive Pseudolite Signal Structure,

5) Review Existing UE Requirements Specifications,

6) Review of Shipboard Equipment Specifications,

7) Derivation of Flight Safety Concepts,

8) Derivation of CDU Entry and Display Requirements,

9) Derivation of Flight Instrument Interface Requirements,

10) Derive Shipboard Equipment Requirements,

11) Derive DGPS UE Requirements,

12) Generation of a System Specification.

The results of Tasks 1 through 7 and Task 10 were originally documented in CDRLs A001 and A002.[1] Updates were made to the documentation of these tasks in this report based on more recently obtained information. The updated results of those tasks are contained in Sections 2.2 and 2.3 and Appendices II, IV and V of this report. Task 2 (Section 2.2) was updated to include Low Probability of Intercept (LPI) analysis of the JTIDS system and to derive new data link possibilities base on the results of that analysis. Appendix II contains the derivation of the LPI analysis tools for defining LPI requirements. Appendix V was updated to include the LPI analysis for pseudolites. Task 3 (Section 2.3) was updated based on the updated Military Standard 1553 bus interface document the incorporated the expanded Area Navigation (RNAV) requirements into the Miniature Airborne GPS Receiver (MAGR). Appendix IV provides supporting data for that task.

Sections 2.1 through 2.12 document the results of Tasks 1 through 12. Appendix I provides a concept of Differential GPS for Shipboard TACAN replacement, supplementing Sections 2.1 and 2.2. Appendix II is the derivation of Low Probability of Intercept requirements, also supplementing Sections 2.1 and 2.2 as well as Section 2.4. Appendix III provides details of the Joint Tactical Information Distribution System

[1] Minutes of Kick Off Meeting and Preliminary Studies Summary Tasks 1, 2 and 3, 18 January - 13 May 1991, CDRL A001.

Summary of Concept Development Tasks 1 Through 7 and Task 10, 14 May - 12 August 1991, CDRL A002.

(JTIDS), supplementing Section 2.2. Appendix IV provides details of the Military Standard 1553 bus interface data content, supplementing Section 2.3. Appendix V provides a derivation of a pseudolite signal structure, supplementing Section 2.4. Finally, Appendix VI is the GPS System Specification for Shipboard TACAN Replacement, supplementing Section 2.12

1.1 Summary and Conclusions

1.1.1 Summary and Conclusions for Task 1, Review Shipboard TACAN Requirements In this task, Shipboard TACAN Replacement Requirements are reviewed. The requirements reviewed were taken from two sources -- a Tentative Operational Requirements (TOR) document generated by the Navy and an Institute of Navigation (ION) paper presented at ION GPS 90, an excerpt of which is given in Appendix I. These requirements are restated, discussed and summarized. They relate to accuracy, low probability of intercept (LPI), anti-jam (AJ) margin, EMI, data encryption, the number of users, air-to-air range and bearing, cost, integrated logistics support and enhancements. LPI requirements were derived and detailed LPI analysis techniques were derived to support the evaluation of the LPI capabilities of data links. That derivation appears in Appendix II.

1.1.2 Summary and Conclusions for Task 2, Investigation of Existing Data Links Based upon the requirements reviewed and summarized in Task 1, information regarding existing ship-to-aircraft data links are reviewed and compared to the requirements. Most existing data links do not meet the requirements, based mostly on availability, not having an LPI capability, not having an AJ capability, not being secure or being too costly. The most promising existing data link is TADIL J Link-16 (JTIDS), but with modifications to provide a better LPI capability and to reduce aircraft unit costs. A signal structure was derived that results in some modifications to the existing JTIDS terminals to use it, but still be compatible with the existing JTIDS signal structure. This would allow the development of new low cost terminals with reduced data rate and AJ capability and using new technology for those aircraft not outfitted with JTIDS. Shipboard terminals would also have to be modified. This is because JTIDS aircraft terminal costs, as they currently exists, are too high. However, it is believed the modifications to the exiting terminals and the new terminals will meet the cost bogey suggested in the TOR. The LPI capability would also be significantly improved when using the new signal structure. In fact, at the same time, the performance and LPI capability of JTIDS itself would also be improved because of the terminal modifications.

Two new data links are proposed based on a further evolution of JTIDS technology that would meet all requirements of a data link for the Shipboard TACAN replacement and provide even more cost reduction. The data capacity of these new links would be somewhat less than JTIDS, but with a much better LPI capability and at a much lower cost. One of these data links would operate in the LINK-4A UHF frequency band, coexist with LINK-4A and have the LINK-4A compatibility with a data capacity equal to LINK-4A (9600 bps), but with the advantages of LPI, security and AJ capabilities. The other data link would be similar, but would operate in the existing JTIDS and TACAN frequency band. It would coexist with JTIDS, but takes advantage of the fact that TACAN is being replaced. It would not have the JTIDS capability, nor are the existing JTIDS terminals compatible with it without further modification. The requirements that emulate these two new data links are included in the system specification in Appendix VI.

The existence of a Technology Development Program at NADC for the development of a new LPI voice/data communication system is referenced. The LINK-4A compatible system satisfies the requirement for that development. Reference is also made to a new Magnavox secure LPI data link that operates at UHF that could possibly be adapted for this application.

1.1.3 Summary and Conclusions for Task 3, Derivation of DGPS Technique and Associated Data Link Content The ION GPS 90 paper summarized in Appendix describes the DGPS technique for Shipboard TACAN replacement. Airborne GPS receiver area navigation (RNAV) requirements are reviewed to determine how they fit in with that DGPS technique, which is based upon the broadcast of moving waypoints.

The MAGR expanded RNAV requirements for rendezvous operations using moving waypoints and automatic sequencing waypoints meet the requirements for the proposed DGPS technique. Twenty four moving waypoints, or a flight plan made up of up to 24 moving waypoints can be input to the MAGR via the 1553 bus in real time to be used for RNAV functions. These waypoints can all be relative to a ship. These waypoints and flight plans can be used in a "differenced" DGPS mode to emulate the functions of

Shipboard TACAN and much more.

The MAGR RNAV requirements and a draft version of the 1553 bus interface (ICD-GPS-059) for the MAGR were reviewed in detail. That detail is summarized in this report for the purpose of understanding how the 1553 bus interface can be used to implement the Shipboard TACAN Replacement using DGPS. It was found that indeed it could, but with some requirements imposed on the host vehicles mission computer for controlling the MAGR and establishing the necessary protocol with the MAGR and the appropriate data link. These mission computer requirements are included in Section 2.11 and in the system specification of Appendix VI.

1.1.4 Summary and Conclusions for Task 4, Derivation of Pseudolite Signal Structure The concept of pseudolites (PLs) was described. A signal structure was derived that effectively eliminates interference with the GPS satellite signals. This signal is a pulse modulated signal near the L2 GPS frequency that carries a P code like signal. An intentional frequency offset from the L2 frequency, which can be accommodated by the MAGR receiver, further reduces the interference potential. A modification to the shipboards GPS receiver antenna electronics to accept a transmission pulse blanking signal will solve the problem of interference with that receiver. The PL signal structure derived has a reasonable LPI capability because of the P-code bandwidth and its pseudorandom pulsing capability. It could have an excellent LPI capability because of the pseudorandom pulsing capability if the MAGR could be modified to blank noise and interference between the pulses. However, this modification is to its signal processing chip, which may be prohibitive.

Unfortunately, the PL can only be used in a broadcast mode. Thus, although it could provide DGPS information, it cannot be used for RNAV functions. Thus, the use of pseudolites is not recommended. The requirements for using them, however, are included in the system specification of Appendix VI.

1.1.5 Summary and Conclusions for Task 5, Review of Existing User Equipment Requirements Specifications This task only consisted of the review of documents. The documents reviewed are listed and a summary of the information extracted from those documents is included.

1.1.6 Summary and Conclusions for Task 6, Review of Shipboard Equipment Specifications This task only consisted of the review of documents. The documents reviewed are listed and a summary of the information extracted from those documents is included.

1.1.7 Summary and Conclusions for Task 7, Derivation of Flight Safety Concepts Two potential problems relative to flight safety are addressed -- one related to the interference to other systems due to transmitted signals, and one related to the integrity (or correctness) of the signals that are transmitted. Interference is shown to be not a problem. Two techniques are derived for monitoring the integrity of transmitted signals. One of these requires the feedback from the monitoring of the transmitted signal on the ship, while the other requires a feedback from aircraft based on its reception of the transmitted signal. These techniques are factored into the derivation of the overall requirements for the Shipboard TACAN replacement using DGPS in Appendix VI.

1.1.8 Summary and Conclusions for Task 8, CDU Entry and Display Requirements The MAGR does not interface directly with a CDU. The CDU interface is via the 1553 bus and probably via the mission computer. The 1553 bus content was reviewed as part of Task 3, where it was determined that all requirements for Shipboard TACAN Replacement using DGPS are satisfied.

1.1.9 __Summary and Conclusions for Task 9, Derivation of Flight Instrument Interface Requirements__ The ARINC 429 interface document was reviewed and it was determined the interface meets all requirements for the Shipboard TACAN Replacement using GPS. This is not surprising since it is believed that TACAN uses the same interface. On some host vehicles, the MAGR does not interface with the flight instruments. Similar to the CDU, that interface is via the 1553 bus and the mission computer. The 1553 bus interface document was reviewed and it was found that all the data available to the ARINC 429 interface is also available to the 1553 bus interface.

1.1.10 __Summary and Conclusions for Task 10, Derivation of Shipboard Equipment Requirements__ Shipboard equipment requirements are derived for three different options -- the use of a conventional data link for the broadcast of DGPS information, the use of a conventional data link for two-way communication with the aircraft to not only broadcast DGPS information, but to perform an RNAV function, and the use of pseudolites to the broadcast of DGPS information. Only the second option can be used for RNAV because it is imperative to have feedback from the aircraft in an RNAV environment.

1.1.11 __Summary and Conclusions for Task 11, Derivation of DGPS UE Requirements__ As stated above for Task 3, the MAGR meets all the requirements for the Shipboard TACAN Replacement using DGPS, unless pseudolites are used. For that option, the requirements for the MAGR to track pseudolites and collect higher rate data from them are derived and specified. They are also specified as and option in the system specification of Appendix VI.

In addition to the MAGR requirements, it was determined that the host vehicle mission computer and the host vehicle data link terminal also comprise part of the DGPS UE. The mission computer requirements were derived and are summarized in Section 2.11 and detailed in the system specification of Appendix VI. The data link requirements were derived as part of Tasks 2 and 3 and are also specified in the system specification of Appendix VI.

1.1.12 __Summary and Conclusions for Task 12, Generation of a System Specification__ The system specification appears in Appendix VI and is a collection of all the requirements derived in this study. The conclusion is that a two way LPI data link must be developed, not only for the Shipboard TACAN Replacement using DGPS, but for RNAV and air traffic control. It was also concluded that, with the expanded RNAV capability currently being implemented, the MAGR meets all requirements without change for the Shipboard TACAN Replacement using DGPS, unless pseudolites are used. Then, at a minimum, software changes are required.

In addition to the data link and the MAGR, the host vehicle mission computer must play a role in this system. It must interface between the data link and the MAGR and also interface to the CDU and flight instruments. It is assumed that it already does interface with the CDU and the flight instruments. Detailed software requirements will have to be derived for the mission computer and the appropriate changes made.

Shipboard equipment requirements are also specified. Different options were derived depending upon the data link implementation. As with the host vehicle mission computers, the ships external computer and the NTDS Controller will share the burden of interfacing between the ships navigation system, which includes the GPS RCVR-3S, and the new data link. Of course, a data link terminal will also have to be developed for the ship. It is likely that the requirements for the terminal will be different than that for the host vehicle. Those differences are not specified in this report or in the system specification.

A functional block diagram of this DGPS System is provided in Appendix VI.

THIS PAGE INTENTIONALLY LEFT BLANK

2.0 FINAL STUDY RESULTS

In this section, the final results of studies defined by Tasks 1 through Task 12 are provided. For completeness, a description of those tasks as stated in the Statement of Work are as follows:

Task 1 - Review of Shipboard TACAN Requirements

It is anticipated that NADC has personnel with extensive experience with shipboard TACAN, and also has extensive documentation on the system. AJ Systems proposes that a dialogue be set up with these personnel in order to review the features of that system, and then translate the important features into requirements for its replacement. This is probably not an extremely important task, but worth a nominal amount of time to provide a starting place for deriving requirements for the replacement system. AJ Systems proposes to travel to NADC for a contract kickoff, spending 2 to 4 days at NADC covering a variety of tasks. It is proposed that a few hours of that time be spent on this task, plus some time reviewing any existing documentation. Any worthwhile documentation will be requested by AJ Systems.

A short summary of this review and how it relates to the replacement system requirements will be provided to NADC. The most important outputs of this task are anticipated to be in the area of CDU and flight instrumentation interface requirements, plus flight safety requirements.

Task 2 - Investigation of Existing Data Links

It is also anticipated that NADC has personnel with extensive knowledge of ship-to-aircraft data links, and how those data links might interface with the UE (such as via a 1553 bus). Just as in Task 1, AJ Systems proposes that a dialogue be set up with these personnel to establish the capability of existing data links, if any, to provide DGPS information from the ship(s) to the UE, including encryption capabilities. Documentation on promising data links will be requested and reviewed.

A summary of this investigation will be provided to NADC. If the findings are positive, interface requirements will be derived from the data link system to the UE, and the system will be considered as an alternative to a pseudolite system.

Task 3 - Derive DGPS Technique and DGPS Data Link Data Content

The DGPS technique recommended by the RTCM Special Committee 104 (broadcast of pseudorange corrections) is not appropriate for this application, since it requires a reference station that is stationary with a known location. A more appropriate technique is to broadcast the ship location(s), use that location as a moving waypoint, causing the UE to steer the pilot to the ship. This technique is only DGPS in the sense that the navigation is relative to the ship, provided that the UE location is derived similar to that of the ship location(s). That is, did the UE use the same SVs in his solution that the ship did? The purpose of this task is specify the technique to be used, but more important, to specify the data to be sent to the UE. For example, should the SV IDs used by the ship's equipment be transmitted to the UE to ensure that the UE uses the same SVs, and thus providing a true DGPS operation? Other data content might include the heading of the ship's runway to provide extra guidance information to the UE.

Since the ship's location, velocity and heading are sensitive information, encryption of the DGPS data will probably be required. It may be appropriate to use the same techniques used for encrypting GPS SV data in this case, in order to minimize the impact on UE design. Of course, NSA approval would be required. AJ Systems proposes to document a strawman technique for encryption and provide it to NADC. Since this documentation will be classified, a DD-254 will be required as part of the contract.

The output of this task is, of course, the data structure of the DGPS signal. In addition to the documentation of the strawman encryption technique, AJ Systems will provide a white paper describing the derived data structure.

Task 4 - Derive Pseudolite Signal Structure

It is a given that one of the proposed data link alternatives will make use of a pseudolite with a signal structure similar to that of the GPS satellites at or near one or both of the GPS frequencies.

AJ Systems has studied this alternative extensively, and has already derived strawman signal structures. This is an important task in that using pseudolite signals can cause two major problems for the UE -- both based on the infamous near-far problem. These problems are the fact that the pseudolite can interfere with the reception of the SV signals (and other pseudolite signals as well), and the fact that the received signal strength received from the pseudolite can vary significantly with distance from it, causing UE dynamic range problems. This problem has been addressed by the RTCM[2] and revisited by AJ Systems[3] for civil applications. The later addresses the affects of C/A code pseudolites on Phase III GPS UE, a subject basically ignored by the former. As it turns out, the problem is not quite so severe for the military application because P codes can be used, which provide 15-20 dB more cross-correlation margin and more anti-jam capability than do the C/A codes. In fact, AJ Systems has derived a P code version of a pseudolite signal structure that appears to be compatible with the Phase III UE.

The effect of pseudolites on the Phase III UE, as determined by the studies of AJ Systems mention above, are based on the knowledge of that UE by AJ Systems. This knowledge may not be exactly correct. Thus, it is proposed that the studies be "fine-tuned" as part of this SBIR program, using Phase III UE design information provided by NADC. The results of this "fine-tuned" study will be provided in a white paper.

Task 5 - Review Existing UE Requirements Specifications

This task consists of reviewing exiting UE specifications and interface documents to determine the UE capability to operate in a DGPS environment and/or with pseudolites, and to determine what changes to the UE are required to operate in a DGPS environment and/or with pseudolites. The goal will be to minimized changes, so this review will take place early in the program so that the new specified requirements will have a minimal impact on the current UE design.

As a minimum, the specifications (latest versions) to be reviewed are as follows:

1) RCVR3A Prime Item Development Specification

2) RCVR3A Computer Program Development Specifications

3) RCVR-3AM System Specification

---

[2]Thomas A. Stansell, Jr., "RTCM SC-104 Recommended Pseudolite Signal Specification", Global Positioning System, Volume III, The Institute of Navigation, Washington, DC, 1986.

[3]A. J. Van Dierendonck, "The Role of Pseudolites in the Implementation of Differential GPS", Record of the Position Location and Navigation Symposium, PLANS '90, Las Vegas, Nevada, 20-23 March 1990.

4) RCVR3A Computer Program Product Specification

5) RCVR3A Prime Item Product Specification

6) Prime Item and Computer Program Development and Product Specifications for CDUs used with the RCVR3A (assumed to be the C-11702/UR Indicator ANVIS Light Control).

7) ICD-GPS-059, MIL-STD-1553 Multiplex Bus Interface

8) ICD-GPS-073, Digital Flight Instruments (ARINC 429) Interface

9) RCVR3A Operator's Manuals

10) Any other specification that NADC feels applies.

This list of applicable specifications will be finalized at the contract kickoff meeting at NADC. At that time, the list of documents in NADC's GPS library will be reviewed by AJ Systems, and a request will be made for the applicable specifications.

A summary of this review and how it relates to the replacement system requirements will be provided to NADC. The findings of this review will be factored in the derivation of requirements for the UE using DGPS and pseudolites (Task 11).

Task 6 - Review of Shipboard Equipment Specifications

To replace the shipboard TACAN with DGPS, with or without a pseudolite, the ship's GPS location and velocity must be transmitted to the aircraft. It may be possible to use the RCVR3S for the derivation of that location and velocity, although, if a pseudolite ranging capability is specified, a self-contained pseudolite GPS receiver may be more appropriate because of time synchronization requirements. If an existing data link is specified, information from the RCVR3S must be transferred to that data link, probably via the NTDS (MIL-STD-1397A). Even the pseudolite would interface to some system via the NTDS.

This task consists of reviewing applicable shipboard specifications. Guidance from NADC will be required to define what the applicable specifications are. As a minimum, the specifications (latest versions) to be reviewed are as follows:

1) RCVR3S Prime Item Development Specification CI-RCVR-3011A

2) RCVR3S Computer Program Development Specification CP-RCVR-3011A

3) ICD-GPS-176, Shipboard External Computer (MIL-STD-1397A) Interface

4) MIL-STD-1397A, Input/Output Interfaces, Standard Digital Navy Systems

5) Other applicable specifications

This list of applicable specifications will be defined at the contract kickoff meeting at NADC, but probably won't be finalized until some later date after more is learned about the existing data links. A request will be made by AJ Systems for the applicable documents.

A summary of this review and how it relates to the replacement system requirements will be provided to NADC. The findings of this review will be factored into the derivation of requirements for the shipboard equipment (Task 10).

Task 7 - Derivation of Flight Safety Concepts

Flight safety is equivalent to what the FAA calls integrity of signals-in-space for use in the National Airspace System.[4] The FAA provides this integrity for VOR/DME by monitoring its signals, verifying its performance and terminating its transmission if it is out of tolerance. It is unknown by AJ Systems how this is accomplished, or if it is, in the shipboard TACAN system, but it is conceivable that it could be done the same way. Actually, DGPS can operate in the same way. A monitoring system could be installed on the ship that monitors either the data link signal, or a pseudolite signal, and feeds back the information to the DGPS equipment. If erroneous information is being broadcast, necessary action takes place, such as terminating transmission.

Pseudolite signals provide additional information in that they provide ranging information. Measured range should agree with computed range, and thus, some self-integrity is available without external monitoring. However, external monitoring might also be necessary.

In this task, AJ Systems will expand upon these concepts and investigate other concepts for flight safety. This will include investigating concepts on how the information is displayed to the pilot of the aircraft, or other possible warning mechanisms.

A white paper describing the derived concepts will be provided to NADC for review. In addition, requirements for the implementation of a chosen concept will be included in the shipboard TACAN replacement System Specification.

Task 8 - Derivation of CDU Entry and Display Requirements

Using inputs from the review of existing UE specifications as a starting point, CDU entry and display requirements will be derived for use of the CDU in the DGPS environment. This includes, as a minimum, the entry of mode, ship identification, and display of steering information and flight safety information. It is suspected that many of the required capabilities exist in the RCVR3A, but required upgrades will be specified.

A white paper describing the CDU entry and display requirements will be provided to NADC for review. These requirements will be factored into the shipboard TACAN replacement System Specification.

Task 9 - Derivation of Flight Instrument Interface Requirements

Using inputs from the review of existing UE specifications as a starting point, flight instrument interface requirements will be derived for use in the DGPS environment. It is suspected that the required capabilities already exist in the RCVR3A, but required upgrades will be specified. It is suspected that the ARINC 429 interface specified for the RCVR3A is the same interface specified for modern TACAN sets.

A white paper describing the flight instrument interface requirements will be provided to NADC for review. These requirements will be factored into the shipboard TACAN replacement System Specification.

[4]Ronald Braff and Curtis Shively, "GPS Integrity Channel", Global Positioning System, Volume III, The Institute of Navigation, Washington, DC, 1986.

Task 10 - Derive Shipboard Equipment Requirements

Based on the review of shipboard specifications, the derived DGPS requirements for both conventional data links and pseudolites, and the derived flight safety requirements, shipboard equipment requirements will be derived for the implementation of the TACAN replacement. These requirements will define the existing shipboard equipment that will be used in the system, the interfaces to existing equipment and requirements for new equipment, including monitors for flight safety.

A white paper describing the shipboard equipment requirements will be provided to NADC for review. These requirements will be factored into the shipboard TACAN replacement System Specification.

Task 11 - Derive DGPS UE Requirements

Updates to the UE Prime Item and Computer Program Development Specifications will be derived to

1) interface with a data link to accept DGPS inputs

2) receive pseudolite signals

3) derive DGPS inputs from pseudolite signal data

4) verify flight safety from received inputs

5) accept inputs from the CDUs and 1553 bus in order to operate in the DGPS environment

6) provide information to the pilot via the CDUs, flight instruments and 1553 bus for navigation with respect to the ship(s).

Theses updates will be provided to NADC as changes to the UE RCVR3A specifications for review, and then factored into the shipboard TACAN replacement System Specification.

Task 12 - Generation of a System Specification

Outputs of Tasks 3, 4, 7, 8, 9, 10 and 11 will be organized into a stand-alone System Specification for the shipboard TACAN replacement. The specification will be organized into two parts -- one using a conventional data link to transmit DGPS information, and one using pseudolites to transmit DGPS information. This System Specification will also serve as the final report for this SBIR program.

Of course, based on the Kick Off Meeting and because of work performed by both NADC and AJ Systems prior to the award of the contract, some of the intent of these tasks has changed somewhat. Those changes will be reflected in the discussions that follow. Also, because a DD-254 was not issued as part of the contract, encryption techniques will only be addressed at a very high unclassified level.

THIS PAGE INTENTIONALLY LEFT BLANK

2.1 Review of Shipboard TACAN Requirements

This task would be better called a Review of Shipboard TACAN Replacement Requirements because it is desired that the replacement system far exceed the capabilities of Shipboard TACAN. The documents that express those desires is the Tentative Operational Requirements (TOR) for Sea-Based Tactical Air Navigation (TACAN) Replacement. These requirements were apparently derived by the Department of the Navy Space and Naval Warfare Command PMW 142 office. These requirements are summarized below.

Prior to contract award, AJ Systems also derived Shipboard TACAN Replacement requirements and published them in a paper.[5] Excerpts from that paper describing those requirements are included in Appendix I.

2.1.1 Summary of TOR Requirements In the TOR general description of the operational requirement, it states the following:

> "With the utility of TACAN thus reduced, a GPS-compatible air-to-ship navigation means is required to (1) effectively aid military aircraft in locating and performing relative navigation to Navy ships at sea, (2) incorporate advance system design consistent with weight, volume, and electromagnetic interference constraints, (3) systematically defeat hostile detection, identification, and targeting, and (4) utilize the military aircraft GPS receiver/navigation set to maximum extent practicable (thereby optimizing the fleet-wide investment in aircraft GPS receiver sets)."

This basically summarizes the operational requirement. The TOR goes on to emphasize the third operational requirement, stating that the "Development of a TACAN replacement must include consideration for electromagnetic emissions (EMCON). Enemy detection of surface units by active, or semi-active signature producing navigation aids must be precluded to the maximum extent practicable, while providing a reliable navigational base reflecting a ships ever changing position."

2.1.1.1 Desired Capabilities After listing the shortcomings of the existing TACAN system (which has continued broad-based signature transmissions emitting from TACAN equipped ships), the range of capabilities desired are listed. These capabilities are as follows:

1) Provide a range/azimuth and level of accuracy equal to or better than present day TACAN (±0.1 nm within 5 *(50)* nm range of the transmitter; ±0.2 nm from 50-390 *(300)* nm range; and overall azimuth accuracy of ±3° line of sight limited). The *(50)* and *(300)* corrects assumed typographical errors in the TOR based on actual TACAN specifications.

2) Electromagnetic emissions must be minimized to present a low probability of intercept (LPI).

3) Operate and meet requirements while operating in the EMI environment of its intended use and in a hostile ECM environment.

4) Operation shall not degrade the performance of other platforms or force systems.

5) Operation shall gracefully degrade in the event of GPS signal loss.

6) Transmitter operation should be variable from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height with fixed, rotational, random, raster or jitter illumination to enhance LPI

---

[5] A. J. Van Dierendonck, "Concepts for Replacing Shipboard TACAN with Differential GPS", Proceedings of ION GPS-90, the ION Satellite Division 3rd International Technical Meeting in Colorado Springs on 21 September 1990.

qualities.

7) An unlimited number of units should be able to use the system.

8) Air-to-air range and bearing should be evaluated.

The TOR expands the requirements to reduce transmission detection and preclude beaconing, interception, jamming and intrusion (MIJI) by suggesting the use of data link encryption, emergency override or directional elevation.

Although the TOR does not address ship-to-ship range and bearing, that also should be evaluated, even though the Navy ships themselves never used TACAN for relative navigation. Other than the cost of software integration, there is no reason why the ships could not use DGPS for that purpose, once it is implemented for aircraft use. Of course, the operating range would be limited to line-of-sight visibility.

2.1.1.2 Cost Goals The TOR then goes on to list affordability limits and estimated funding required for system development. These are:

1) RDT&E cost of $60 million.

2) Sea-based unit cost of $500,000 each.

3) Aircraft incremental unit cost of $25,000 each.

4) Life cycle cost of $540 million for 5 years of operation, including procurement, installation, RDT&E, and 5 years of operating and maintenance costs.

If the sea-based TACAN replacement is not GPS airborne receiver system compatible, an additional $150,000 per aircraft unit cost and $2,300,000,000 in life cycle costs were estimated.

2.1.1.3 Estimated Quantities Approximately 320 ships was estimated for installation. The designations for these ships are CV, CV(N), DDG, DD, CG, CG(N), MHC, LHD, AO, T-AGOR, LPH, FFG, FF, ARS, LCC, LHA, LKA, ATS, LST, AFG, LSD, LPD, AFS, AE, T-AE, AOR, AOE and T-AFS. These designations are important when considering existing data links that may or may not be available on all designations.

Approximately 4,000 aircraft would be affected.

2.1.1.4 Integrated Logistics Support (ILS) The TOR stated that a significant reduction in ILS costs could be expected with a GPS compatible TACAN replacement as compared with support of aging TACAN equipment. It went on to state the ILS requirements, but at this point, these requirements are beyond the scope of this study except to note that the objective is to minimize the cost of ILS and to identify and specify "design to" requirements necessary to ensure operational supportability.

2.1.1.5 Related Efforts The TOR stated that no preference is given to GPS when considering solutions for relative navigation. Modifications to the existing TACAN system to fully meet the requirement, JTIDS, and all other potential solutions must be investigated. However, these investigations would be out of the scope of this study; but, comments on the two systems mentioned will be made.

The TOR also described the concept of GPS pseudo-satellites (pseudolites), which will be addressed in Task 4 of this study. Pseudolites are definitely a candidate to aid in the replacement of shipboard TACAN. The TOR stated that foreign systems should also be included in the analysis during preparation of the DOP. This is also considered out of the scope of this study.

Other efforts were also listed in the TOR. Again, investigation of these efforts is considered out of the scope of this study.

2.1.2 Summary of Requirements Described in ION Paper Independent of the TOR described above, the subject paper discussed Shipboard TACAN concepts. Appendix I is an edited excerpt from that paper, which also provides a description of the DGPS concept, a subject of Task 3 of this study.

2.1.3 Comparison of TOR and ION Paper Requirements For the most part, the TOR and ION Paper agreed on the requirements and desired capabilities for the Shipboard TACAN replacement. The following differences are noted.

1) The ION paper did not include the desired capability to "spotlight" transmitter transmissions to enhance LPI qualities.

2) The ION paper did not call for an unlimited number of units to be able to use the system. However, that capability was implied.

3) Air-to-air range and bearing was not addressed in the ION paper.

The impact of the first of these three differences would probably be the use of a beam-steering phased array antenna on the ship for DGPS transmissions. That possibility will be addressed in this study as part of future tasks.

The capability of the second difference may be impacted by system enhancements to include Air Traffic Control. This enhancement is a future subject of this study.

The impact of the third difference is that the aircraft would be required to transmit, which increases the cost of the aircraft units. This later capability does exist with TACAN, but with the addition of pilot-to-pilot communications to indicate aircraft heading. Air-to-air range and bearing capabilities will be addressed in this study.

2.1.4 Summary of Shipboard TACAN Replacement Requirements The TOR best states the overall requirements for the Shipboard TACAN Replacement, namely to provide a means to :

1) Effectively aid military aircraft in locating and performing relative navigation to Navy ships at sea

2) Incorporate advance system design consistent with weight, volume, and electromagnetic interference constraints

3) Systematically defeat hostile detection, identification, and targeting

4) Utilize the military aircraft GPS receiver/navigation set to maximum extent practicable, thereby optimizing the fleet-wide investment in aircraft GPS receiver sets.

The following is a summary of a combination of the TOR requirements and desired capabilities and those listed in the ION paper:

1) Accuracy: The replacement system shall provide a range/azimuth and level of accuracy equal to or better than ± 0.1 nm within 50 nm range of the ship; ± 0.2 nm from 50-300 nm range; and overall azimuth accuracy of $\pm 3°$ line of sight limited. The replacement system shall improve that accuracy consistent with the capabilities of "Differenced" DGPS and data transmission bandwidth. Accuracy shall degrade gracefully in the event of GPS signal loss or the loss of DGPS messages, including loss of either GPS or DGPS data link signals due to multipath and antenna masking. Con-

straints on data transmission rates shall be a trade-off against DGPS accuracy.

2) Low Probability of Intercept (LPI): Electromagnetic emissions must be minimized to present an LPI capability. Variable transmitter operation shall be considered to cover from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height with fixed, rotational, random, raster or jitter illumination to enhance LPI qualities. Advantage of spread spectrum communications shall be exploited so that transmission energy can be spread over a wide frequency range to provide the capability to receive signals well below ambient noise, thus making the signal more difficult to detect by unfriendly forces, including the encryption of the "spreading" code.

3) Anti-Jam (AJ) Margin The system shall operate and meet requirements while in the EMI environment of its intended use and in a hostile ECM environment. AJ margin shall be a trade-off against LPI capability.

4) EMI: Operation of the replacement system shall not degrade the performance of other platforms or force systems, including the performance of both the shipboard and aircraft GPS receivers.

5) Data Encryption: The replacement system shall reduce transmission detection and preclude beaconing, interception, jamming and intrusion (MIJI) with the use of data link encryption. Data encryption shall prevent any unauthorized individual obtaining the information in the DGPS data link message, primarily the location of the ship. If possible, employ the encryption techniques used on the GPS signals from the satellites, so that the same keys can be used, thus minimizing the impact on implementation of encryption, subject to the endorsement by the National Security Agency (NSA).

6) Number of Users: An unlimited number of units shall be able to use the system.

7) Air-to-Air Range and Bearing: The capability to perform air-to-air range and bearing shall be evaluated.

8) Cost Goals: The replacement system shall provide these capabilities with the following cost guidelines:

1) RDT&E cost of $60 million.

2) Sea-based unit cost of $500,000 each.

3) Aircraft incremental unit cost of $25,000 each.

4) Life cycle cost of $540 million for 5 years of operation, including procurement, installation, RDT&E, and 5 years of operating and maintenance costs.

These cost goals shall be based on installation on approximately 320 ships with the following designations: CV, CV(N), DDG, DD, CG, CG(N), MHC, LHD, AO, T-AGOR, LPH, FFG, FF, ARS, LCC, LHA, LKA, ATS, LST, AFG, LSD, LPD, AFS, AE, T-AE, AOR, AOE and T-AFS, and for installation in approximately 4,000 aircraft of various types.

9) Integrated Logistics Support: The objective shall be to minimize the cost of ILS and to identify and specify "design to" requirements necessary to ensure operational supportability.

10) Enhancements: Enhancements to provide improved accuracy and air traffic control shall be considered.

2.1.5 Low Probability of Intercept Requirements Revisited LPI requirements are the key requirements for the replacement of Shipboard TACAN with DGPS. As will become evident throughout this report, all of the other derived requirements will be easier to meet than are the LPI requirements. Most of the existing US Navy data links do not meet the LPI requirements. One possible exception is the Joint Tactical Information Distribution System (JTIDS), depending on how one defines LPI. Thus, it is appropriate here to expand the idea of LPI, because LPI itself is ill defined. This expansion is presented in Appendix II.

THIS PAGE INTENTIONALLY LEFT BLANK

2.2 Investigation of Existing Data Links

A data link reference manual[6] was provided to AJ Systems for review. This manual contains summary description sheets of selected fleet communication links including any relationship the link has to the transfer of navigation information. These sheets contain an overview of specific link parameters, characteristics, and applications as well as any other amplifying information that may be applicable for understanding the link. A most important characteristic described was the designations of the user ships and user aircraft on which each link was used.

AJ Systems reviewed this document to determine the applicability of the summarized links for the broadcast of DGPS information for the Shipboard TACAN replacement. The following is a discussion of that review.

Most of the links summarized in the document were either only applicable to ships, or were specialized and present on very few aircraft, such as, for example, the P3C only. These links were not considered. The following are those that are at least jointly present on a number of ships and aircraft:

1) TADIL C, Link-4A, Naval Tactical Data System (NTDS) - LINK-4A

2) TADIL A, Link-11, Naval Tactical Data System (NTDS) - LINK-11

3) TADIL J, Link-16, Joint Tactical Information Distribution System (JTIDS)

4) TADIXS, Tactical Data Information Exchange Subsystem (TADIXS)

5) MILSTAR, Military Strategic, Tactical and Relay (MILSTAR)

2.2.1 TADIL C, LINK-4A LINK-4A is the NATO designation of TADIL C. It is a one or two way non-secure data link between surface air control stations and controlled aircraft. TADIL C is on most current Navy aircraft and on carriers. It is used for aircraft intercept, traffic control and carrier approach control. It operates in the UHF Frequency Band from 225-400 MHz using an NTDS digitally coded Frequency Shift Keying (FSK) modulation. TADIL C would be an ideal data link for broadcasting DGPS data if it were not essentially an old technology data link that has very few of the desired characteristics specified above for the Shipboard TACAN replacement system. For example, it is not at all LPI nor is it secure. Therefore, the TADIL C, LINK-4A is not considered a candidate for the broadcast of DGPS data. However, a Link-4 compatible LPI data link is proposed as a new data link in Section 2.2.7 below.

2.2.2 TADIL A, LINK-11 LINK-11 is the NATO designation of TADIL A. LINK-11 is a tactical data information link (TADIL) employing netted communication techniques and standard message format for the exchange of digital position, identification and control information among airborne, land-based, submarine and shipboard tactical data systems (TDS). TADIL C is on a variety of ships, but its aircraft installations appear to be only ASW type aircraft. In fact, its primary use appears to be that of communicating tactical pictures, air tracks, surface tracks and ASW data of force units. It operates in the same frequency band as TADIL C, but also operates in the HF band between 2-30 MHz. Its signals are Differential Phase-Shift-Keying (DPSK) of parallel data tones. The link is encrypted.

As with TADIL C, LINK-11 is not at all LPI, although it is secure. However, unlike TADIL C, it is not used for air traffic or approach control. The link is loaded down with tactical information and is not available for the broadcast of DGPS data. Thus, TADIL A, LINK-11 is not considered a candidate for the broadcast of DGPS data.

---

[6] Data Link Reference Manual (Preliminary), Naval Air Development Center, 7 July 1989.

2.2.3 TADIL J, LINK-16 LINK-16 is the NATO designation of TADIL J, and is commonly known as JTIDS (Joint Tactical Information Distribution System). JTIDS is a high-speed voice and digital system that links airborne, shipborne and ground-based units into a tactical communication network providing real-time data base of position, identification, combat status and targeting information. The primary purpose of JTIDS is to manage the air environment with jam-resistant, reliable communications. JTIDS is installed on carriers and on more modern aircraft, such as the E-3A, F-15, F/A-18, F-14 and the E-2C. JTIDS operates at L-Band in the range of 969 to 1206 MHz with notches for IFF at 1030 and 1090 MHz. The link is encrypted many times over. That is, the signal as well as the data is encrypted.

JTIDS, or at least a modified JTIDS, is definitely a candidate for the broadcast of DGPS data. For the most part, it meets all of the requirements specified above, with the exception that it is marginally LPI and that it is relatively expensive. However, with modifications of the shipboard JTIDS terminal transmitters, and with the development of a low cost passive airborne JTIDS terminal, these exceptions can be overcome. The existing airborne JTIDS terminals would be compatible with these modifications.

Because JTIDS, or modified JTIDS, is a viable candidate for use as the data link for Shipboard TACAN replacement using DGPS, its description will be given in detail in Section 2.2.6 and Appendix III.

2.2.4 TADIXS TADIXS (Tactical Data Information Exchange Subsystem) provides integrated worldwide connectivity among the over-the-horizon targeting (OTH-T) community in support of Navy cruise missile operations. It is a one-way transmission to broadcast OTH-T data from shore-based transmitters to recipient transmitters. One-way transmission would be fine for broadcasting DGPS data, but since these transmitters are shore-based, TADIXS is, among other reasons such as LPI, not acceptable for that purpose.

TADIXS B is a classified version of TADIXS.

2.2.5 MILSTAR MILSTAR is still in development. It is a new-generation satellite communications system providing global, secure, jam-resistant, low probability of intercept, and survivable minimum essential wartime communications for strategical and tactical requirements. MILSTAR uses extensive spread spectrum techniques to make it jam resistant. It's transmission frequency is at EHF (44 GHz) to the satellite with a 2 GHz bandwidth, which makes it LPI and jam-resistant. It's transmission is also directional via a narrow beam towards the satellite, which also makes signal detection and triangulation even more difficult, even though the transmission power is quite high.

MILSTAR has the capabilities to meet the requirements as a data link for the Shipboard TACAN replacement, with two exceptions. First of all, it would be reserved for wartime communications for strategic and tactical applications and probably wouldn't be available for area navigation purposes. The second exception is that is it is highly unlikely that a MILSTAR terminal would meet the cost goals specified in the TOR, even if a receive only terminal were developed. This is because it operates at a high frequency with a wide bandwidth, requiring expensive technology for its implementation. Unfortunately, the features that make it LPI and jam-resistant also makes it expensive.

2.2.6 JTIDS Details Details of the JTIDS system are provided in Appendix III for the purpose of describing modifications to the system that would make it appropriate for a data link for the Shipboard TACAN replacement using DGPS. Actually, for the most part, JTIDS, as it exists, satisfies most of the requirements specified above. The two basic requirements it doesn't meet are as follows:

1) JTIDS, although specified as a being LPI as a guide for this study, has limited LPI capabilities. However, with transmitter and receiver modifications, it could be upgraded to meet the intent of the LPI requirement.

2) JTIDS terminals are far too expensive to meet the cost goals of the TOR for aircraft installation.

Although it already exists in some of the Navy's aircraft, it doesn't exist in the entire fleet. However, a new technology receive-only terminal may meet these cost goals.

JTIDS has also been advertised as providing a relative navigation (RNAV) capability by itself.[7] However, in general, this capability is very limited because of geometric considerations. The technique requires multiple participants to be part of the JTIDS net at appropriate locations for good triangulation. A lone aircraft returning to a lone ship could not use such a system, unless the system were combined with GPS. But, then, it suffices to use DGPS and use JTIDS only as a data link providing moving GPS waypoints representing holding patterns, ships' locations, etc.

2.2.6.1 LPI Capability of JTIDS Here, the LPI capability of JTIDS is compared to the requirements specified in the TOR in Section 2.1.1, although absolute requirements were not specified, only desired capabilities. The largest discrepancy of the JTIDS LPI capability with respect to the desired capability is the following, as stated in Section 2.1.1:

> "Transmitter operation should be variable from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height with fixed, rotational, random, raster or jitter illumination to enhance LPI qualities."

JTIDS has none of those capabilities except for the jitter illumination. However, JTIDS has limited LPI capabilities. Using the concepts established in Appendix II, these capabilities are established here.

2.2.6.1.1 JTIDS LPI Capabilities Evaluation In Appendix II, some of the concepts established for evaluating LPI capabilities of a data link were applied to JTIDS as an example. In this section, this applications will be expanded.

The probabilities of detection for both the user and the interceptor are presented in Figure 1. These probabilities are evaluated using the JTIDS parameters presented in Appendix III. They are plotted versus distance from the transmitter in Figure 1. The JTIDS parameters for this evaluation are as follows:

1) $N_{0i} = 10 \log_{10} KT + L_i + NF_i = -204 + 1 + 3 = -200$ dBw/Hz (Noise density of interceptor receiver),

2) $N_{0u} = 10 \log_{10} KT + L_u - NF_u = -204 + 8(1) + 2 = -194(-201)$ dBw/Hz (Noise density of JTIDS terminal -- two cases, one with 8 dB cable loss and one with 1 dB cable loss),

3) $B_u = 156.25$ kHz (Acquisition predetection bandwidth of JTIDS terminal),

4) $B_i = 153$ MHz (Predetection bandwidth of interceptor receiver),

5) $IL_u = IL_i = 2.5$ dB (Implementation Losses)

7) $T_u = \frac{32}{B_u}$ (Post-detection interval of 32 pulses for JTIDS acquisition),

8) $T_i = 258 \times 6.4\ \mu$seconds $= 1.6512$ mseconds (7.8125 mseconds) (Post-detection interval for interceptor, 2 cases, one for correlating interceptor and one for non-correlating interceptor),

---

[7]See for example, Walter R. Fried, "Operational Benefits and Design Approaches for Combining JTIDS and GPS Navigation", Navigation: *Journal of The Institute of Navigation*, Vol. 31, No. 2, Summer 1984.

9) f_o = 1206 MHz,

10) c = 161,875 nm/second (speed of light),

11) P_{PK} = 200 watts,

12) PDC_U = 1 (Effective user pulse duty cycle - accounted for in T_U),

13) PDC_i = 1(0.21135) (Effective interceptor pulse duty cycle -- two cases -- one for correlating interceptor and one for non-correlating interceptor = $\frac{258 \times 0.0064}{7.8125}$).

The probability of false alarm was taken to be much larger for the interceptor than for the user. This is reflected in the resulting decision signal-to-noise ratio.

The second user case reflects a terminal improvement that could be made by placing a low-noise-amplifier at the antenna, thus eliminating most of the cable loss. The two interceptor cases reflect complexity of the interceptor's terminal. In one case (correlating), the interceptor takes advantage of the knowledge of the JTIDS fixed pulse pattern by correlating to that pulse pattern. This is done using the same techniques as the JTIDS terminals use, except at a much wider bandwidth.

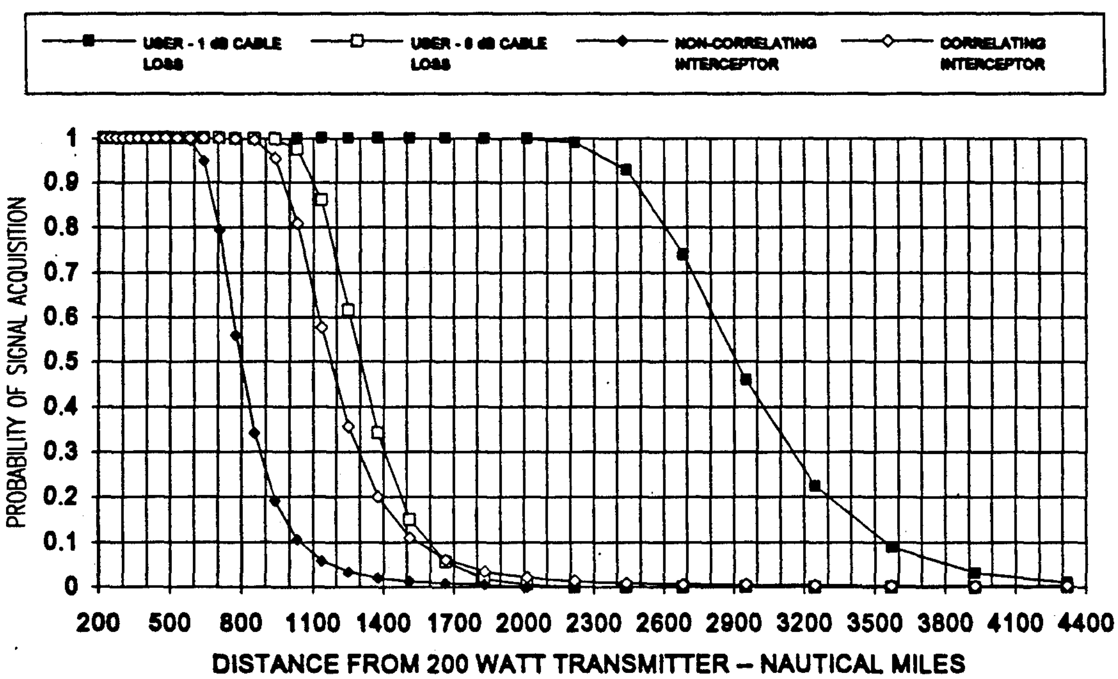

Figure 1. Probability of User and Interceptor Detecting JTIDS Signals

From Figure 1, we can evaluate the ratio of distances of detection between the user and the interceptor $\frac{d_u}{d_i}$.

The worst case ratio of the four possible ratios that can be evaluated is that between the user with an 8 dB cable loss and the correlating interceptor, which is very near 1. The best case ratio is between the user with a 1 dB cable loss and the non-correlating interceptor, which is approximately 3, which isn't too bad. It is obvious that with a little work JTIDS can provide an LPI capability.

Figure 2 presents the Decision Signal-to-Noise ratio for the same cases evaluated using Equation II.15 of Appendix II. From this figure, we can conclude that ratio to be consistent for both cases of the user and both cases of the interceptor, where the evaluation provides the following:

1) SNR_{DU} = 18.5 dB (Required signal-noise ratio for JTIDS acquisition),

2) SNR_{Di} = 12.8 dB (Required signal-to-noise for interceptor acquisition).

These quantities differ because of differences in assumed performance for the user and the interceptor. Also, from Appendix III, we have that the required signal-to-noise ratio (SNR_{ur}) for JTIDS acquisition is 15 - IG = 15 - 11 = 4 dB, or 2.512 in ratio.

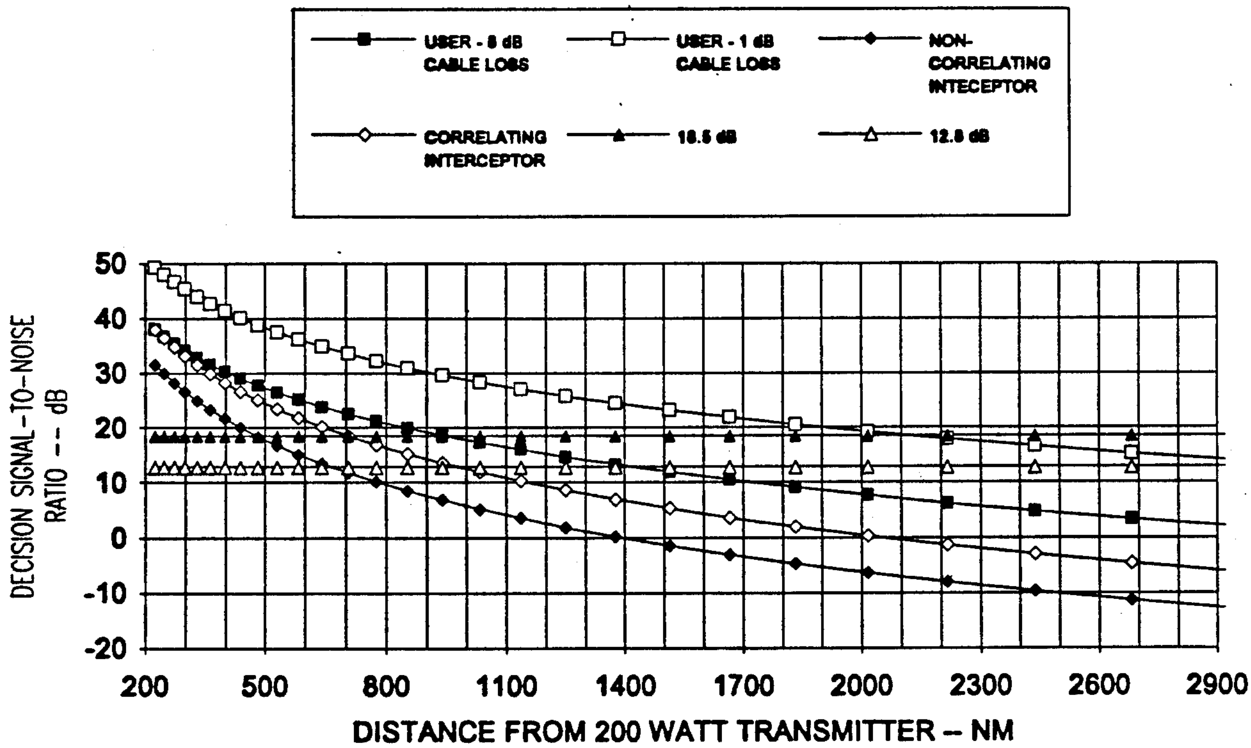

Figure 2. Decision Signal-to-Noise Ratio for User and Interceptor

Then, evaluating the distance ratios using Equation II.19 of Appendix II, we have the four ratios:

1) $\frac{d_u}{d_i}$ = 0.9572 (8 dB user cable loss versus correlating interceptor),

2) $\frac{d_u}{d_i}$ = 1.412 (8 dB user cable loss versus non-correlating interceptor)

3) $\frac{d_u}{d_i}$ = 2.143 (1 dB user cable loss versus correlating interceptor),

4) $\frac{d_u}{d_i}$ = 3.161 (1 dB user cable loss versus non-correlating interceptor).

Since these numbers were derived using the same parameters to generate Figures 1 and 2, they are in excellent agreement with Figure 1. However, Equation II.19 provides a numerical alternative to "eye-balling" those ratios from Figure 1.

These results show that JTIDS, as presently configured, has a marginal LPI capability against either a non-correlating or correlating interceptor. However, if the terminals were modified to include low-noise-amplifiers at the antenna, the LPI capability could be improved by a factor of 2 or more. This capability could be improved even more with other modifications, which are discussed below.

2.2.6.1.2 Enhancement of JTIDS LPI Capability With Shipboard Transmitter Modifications The main reason the JTIDS LPI capability is limited is because it was designed to have a good AJ capability. Furthermore, it was designed as a tactical communication system to be used in a time of conflict. In fact, if the Naval fleet or aircraft are worried about being detected, it would definitely turn off the JTIDS transmitters, rendering it useless as a tactical communication system anyway. With this in mind, one could postulate modifications to JTIDS where it could have an important, but limited, use (such as a data link for Shipboard TACAN replacement using DGPS) and have desirable LPI capabilities. For example, shipboard JTIDS terminals could be modified to meet the TOR requirements (but not airborne terminals). This could be accommodated by replacing the power amplifiers and antennas with variable power amplifiers and steerable beam phased-array antennas.

As was indicated in Appendix III, Section III.4.2, there is already some margin in the received power in the absence of jamming, to the point where the transmitted power could be reduced, if required, by a factor of 4 to 50 watts. This would reduce the probability of intercept sphere radius by a factor of 2. Also, if the transmitted power were variable, the range of the system is simply reduced. For example, as was stated in Section 2.1 above, the required range of the Shipboard TACAN replacement was set at 50 nm, with a desired range of 300 nm. Thus, the transmitted power could be reduced another 15.56 dB to 1.39 watts at critical times and reduce the probability of intercept sphere radius by another factor of 6. In fact, there is no reason why the power can't be reduced even more if required with the effect of a further reduction in range.

The enhancements realized by using a steerable beam phased-array antenna are obvious. If one were to increase the gain of the transmitting antenna by 20 dB in the desired direction over that of the other directions, the probability of intercept sphere radius would be reduced by a factor of 10 in the other directions.

If at times when LPI is desired, the only use of JTIDS is to replace Shipboard TACAN using DGPS, the amount of transmission would also be reduced, in that messages only need be transmitted once every few seconds, thus further reducing the probability of intercept. In fact, with software changes to the JTIDS terminals, the assigned time slots could be randomized using the encryption capability of JTIDS.

2.2.6.1.3 Improving The LPI Characteristics Of JTIDS Terminals JTIDS as utilized by the Navy requires the use of a 258 pulse message. A transmitter power of 200 watts peak in conjunction with a 10 dB noise figure receiver are required to meet the normal communications range of 300 nm with some AJ margin. As shown above in Section 2.2.6.1.1, intercepting this message can be performed at a greater range. Another way of interpreting the results presented in Section 2.2.6.1.1 is that intercept can take place at lower signal levels then are required to communicate. There are, however, improvements that can be made to the

JTIDS terminals and the signal message structure that can significantly improve the LPI capability of JTIDS. This requires some moderate modifications to the existing JTIDS terminals, but allows the development of a JTIDS Derivative terminal that is much lower in cost, to the point where the cost goals for the Shipboard TACAN Replacement using DGPS can be met.

Noise Figure Improvement First of all, the terminal system noise figure can be improved easily, resulting in an improvement in receiver sensitivity. Improving receiver system noise figure to 3 dB, including cable loss, will enable transmitter power to be reduced by 7 dB or a factor of 5. Thus the transmitter power can be reduced to 40 watts. This will require terminal hardware modifications, but they are considered to be reasonable and well below the $25,000 bogey. These hardware modifications would be as follows:

1) The addition of a low noise amplifier (LNA) at the antenna(s) to set the system noise figure. In the days when the existing JTIDS terminals were developed, the size of the LNA (and circulator between the antenna and the LNA) made it prohibitive, even thought the E-3 aircraft do use them. With today's technology, however, this is no longer a problem.

2) Insertion of a programmable attenuator in the transmitted signal path to reduce the transmitted power for LPI purposes. This attenuator could be controlled via the 1553 or other available processor bus.

The benefit of this 7 dB reduction in noise figure is shown in Section 2.2.6.1.1, which resulted in a radius of intercept ratio by a factor of 2.24.

Data Modulation Reduction and Randomization Another technique for improving LPI is to reduce the number of pulses in a message from 258 to 63, and to time hop these within the time slot, reducing the radiometric interceptor's energy by 6.1 dB. See Figures III.1 and III.2 in Appendix III for the current pulse modulation waveform and message structures. This start of an evolution to a lower cost LPI data link is illustrated in Figure 3, where it shows the JTIDS message represented at part 1 of the figure with a continuous stream of pulses for 3.354 milliseconds, with pulses occurring every 13 μseconds. This evolves into a message at part 2 of the figure with the same pulses, but only 31 data pulses occurring at random.

There actually remains 63 pulses including 16 single synchronization pulses, 16 header pulses and the 31 information pulses, resulting in one single pulse Reed-Solomon code word as opposed to the lowest capacity three double pulse Reed-Solomon code words. The 4 double time refinement pulses would be eliminated, since most Class 2 terminals don't use them anyway. This modified message structure is feasible at low data rates when it isn't necessary to send all Reed Solomon code words in a single time slot. There is, however, a 2.2 dB loss to the user with respect to using double pulses, so the gain with respect to the interceptor is only 3.9 dB. This results in another reduction in radius of intercept ratio by a factor of 1.57.

Recall that the header of 16 pulses plus the 93 double data pulses, for a total of 202 pulses, are interleaved. For this case where there are only 47 header and data pulses, the remaining pulses would not be transmitted and can be assumed to be zeros in the interleaving process. The transmitter then sends the remaining code word in the interleaved pulse positions which appear to be time-hopped as shown in 2) of Figure 3. Time-hopping causes the interceptor radiometer to integrate noise in addition to pulses during the duration of a message transmission, while the user ignores those known-to-be-zero pulses.

Further gain is then achieved because, for a lower data rate of, say, only 500 bits per second, only one time slot with 31 data pulses out of eighteen time slots on the average is required, which also can be transmitted at random. With 258 pulses in a 7.8125 millisecond message, the duty cycle is approximately 0.21135, and the average non-correlating intercept power is 6.75 dB below the peak power. With 63 pulses, the average power is reduced another 6.1 dB. Furthermore, a pulse correlating interceptor can no longer correlate because the pulse positions are random within a time slot and from time slot to time slot, don't exist on 94.4% of the time slots. The actual capacity is 9600 bits per second, however, if all the times slots are used.

This reduction in the number of pulses requires changes to the existing JTIDS Class 2 receivers, but these changes are software changes. Thus, there is no recurring cost. This is not true, however, for the transmitters. This reasonable modification will require hardware changes in the transmitters to transmission of eliminate pulses.

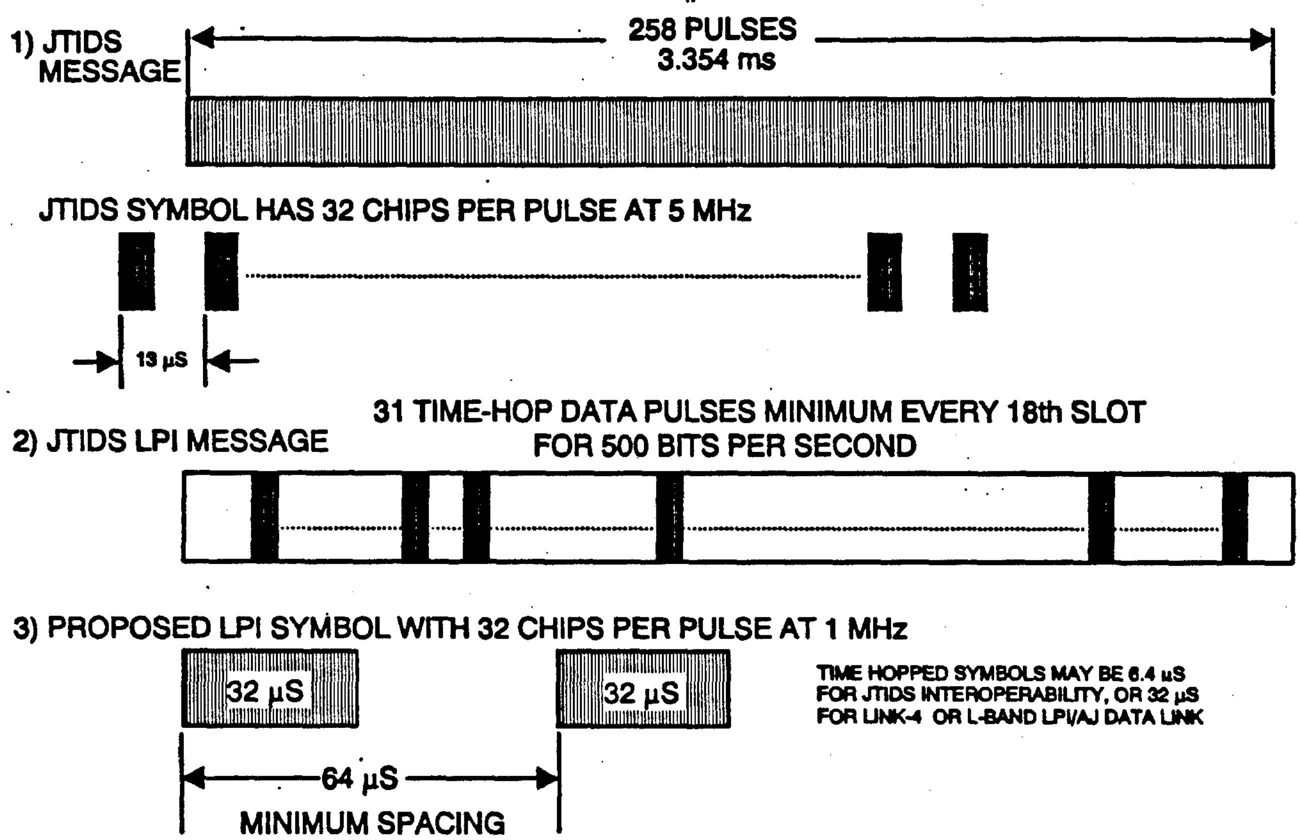

Figure 3. Evolution of JTIDS Signal Structure to an LPI Signal Structure

<u>JTIDS LPI Improvement Summary</u> Taking into account these two techniques, the LPI improvement over conventional JTIDS then becomes equal to 10.9 dB. This is derived from 7 dB less transmitter power due to lower noise figure receivers and 3.9 dB due to the lower density message by limiting the data transmission to one Reed-Solomon code word. The 10.9 dB factor means that the intercept receiver must be closer by a factor of 3.5 than the curves in Figures 1 and 2 indicate, plus the ability to randomize the pulses to prevent interceptor correlation to the pulses. Another way of interpreting the data is as follows: Where the probability of detection for the interceptor is approximately 0.95, the probability of detection is now reduced to approximately zero. The curves in Figure 1 and 2 show that happening with just changing the radius by a factor of 2. For example, the distance ratio of 0.9572 shown for the correlating interceptor against a user with 8 dB of cable loss becomes 3.35, a factor of 3.5 because of the changes in the pulse timing, times a factor of 1.475 because he no longer can be a correlating interceptor for a total improvement of 4.942 in distance. The detection or intercept radius and area are then 0.194 and 0.0375, respectively, of the effective communications radius and area. This is a good LPI capability.

<u>Further LPI Enhancement</u> The pulse density could be reduced even further, if necessary, in a non-jamming environment and in at a reduced operating range. With this reduction, however, the AJ margin is reduced

because all of the power in the Reed-Solomon code is required to process erasures if some of the parity checks are not sent. Recalling from Appendix III that the power of the Reed-Solomon code allows up to 16 symbols to be corrected if they are erasures. Thus, in a high signal-to-noise environment, one can reduce the number of transmitted parity checks for a lower performing code. However, in a high jamming environment the parity checks are required. But, in this environment the radiometric interceptor receiver will also be jammed and not effective.

2.2.6.2 Modified JTIDS Cost Factors The modifications to the JTIDS terminals described above for improving the their LPI capability is obviously in the wrong direction for an the already costly terminals. However, because they are costly, they have not been installed in all of the Navy aircraft. The modifications described above are suggested because, with the data rate changes, a newer low cost terminal (the JTIDS Derivative) can be developed that will satisfy the requirements for DGPS as well as other functions such as air traffic control. These changes are only required to make the existing JTIDS terminals compatible with the proposed signal structure for these newer lower cost terminals. Of course, the newer JTIDS Derivative terminals would not necessarily be able to receive the standard JTIDS signals, and especially not be able to transmitted the standard JTIDS signals. But their purpose would be to augment the current JTIDS system to include DGPS and air traffic control communications with an improved LPI capability.

Even the improvement in noise figure has something to do with the newer lower cost terminals, except that they would be configured with LNAs at the lower cost anyway. The purpose for the improvement in noise figure is to reduce transmission power, which has two benefits. The first is to improve the LPI capability. The second is to reduce the cost of the terminal transmitters. The lower data rate with the lower pulse repetition rate also reduces the cost of the terminal transmitters because the average transmitted power is another 3.9 dB lower. Coupling the two together reduces the average transmitted power by a factor of 12.3, or down to 16.3 watts. This will provide a significant cost savings in a new terminal.

The lower pulse and data rate also reduces the computational load of the terminals to a point where lower cost processors can be used. However, with today's technology, that may not be a significant cost driver.

Other factors that will reduce the cost of the new JTIDS Derivative terminals and still maintain compatibility with the modified existing JTIDS terminals are as follows:

1) Use only one antenna on the top of the host vehicle. The coverage of one antenna is adequate for system operation.

2) Transmit on fewer that 8 frequencies during the synchronization period. This, coupled with the use of only one antenna could reduce the number of receivers from eight in the Class 2 terminal to only one or two. This results in the use of more synchronization pulses on the same frequency for the sync preamble. The current JTIDS synchronization preamble utilizes eight frequencies for the 32 sync pulses to avoid interference to TACAN, which, of course, we are replacing anyway. Furthermore, single antenna operation only requires the use of 16 pulses with a performance is then equal to the data portion of the message.

3) Synchronize the network timing to GPS (or UTC) time. Likewise, synchronize the new terminals to GPS (or UTC) time using the Precise-Time-and-Time Interval (PTTI) output from the MAGR.[8] The shipboard terminals should be synchronize using the PTTI output from the RCVR 3S. This eliminates the need for JTIDS net entry. JTIDS net entry makes use of a message called "Round Trip Timing" (RTT) which is sent and responded to in one time slot. The message utilizes the punctured code format of the header or a 16,5 Reed-Solomon code. The reply provides time and

[8]ICD-GPS-060A, Precise-Time-and-Time-Interval (PTTI) Interface, 2 June 1986

position of the master or any terminal that derived system time from the master. There are 16 levels of system time depending how far removed the donor is from the master. The limiting item on Reed-Solomon decoding speed is the RTT reply. Eliminating this requirement makes it feasible to perform Reed-Solomon decoding using a microprocessor. This decoding is currently performed in hardware. The 16 different levels of system time are also eliminated as well as the need for using a stable oven crystal oscillator, which is relative large and costly.

4) Use the now existing Thornton KGV-8 chip in the signal processor.

5) Last, but not least, use modern technology, ranging from Miniature Microwave Integrated Circuits (MMIC) to single chip agile synthesizers to VLSI ASICs to modern off the shelf microprocessors.

It is highly unlikely that JTIDS terminals with the performance they currently have (AJ, high data rates) could come close to meeting the cost goals specified in Section 2.1.1.2 above, even with modern technology, especially the aircraft incremental unit cost of $25,000 each. Of course, JTIDS already exists on many of the Navy's aircraft as indicated in Section 2.2.3, but not on all. Modifications specified above for those existing terminals would certainly meet those cost goals. Then, if the remainder of the aircraft, plus any new aircraft that do not have JTIDS installed, were outfitted with this newer lower data rate, but with higher LPI capability, JTIDS Derivative terminal, the overall cost goals could be met.

2.2.7 New Data Links As discussed above, the only existing Navy data link that appears to be a candidate to be used as the Shipboard TACAN replacement DGPS data link is Link-16 (JTIDS). If JTIDS Derivative terminal solution described above proves to be unacceptable, or can't be used because of capacity of cost reasons, either a new data link needs to be developed, or some other military data link may have to be used. There has been and indication that a new data link will be developed.[9] This data link, if developed, would be ideal for the Shipboard TACAN replacement DGPS application. In fact, DGPS could possibly provide the information for the automatic carrier landing system.

Magnavox has also developed a new Low Probability of Detection (LPD) hand-held communications transceiver they call "Stealth Comm" that operates in the UHF frequency band (285 to 430 MHz).[10] Although this transceiver may not be suitable as the Shipboard TACAN replacement DGPS data link, the technology used in the transceiver can certainly be extended and applied to this application. It indeed fits in the category of communication system referred to in the *Aviation Week* announcement.

If a new data link is developed just for the purpose of providing DGPS data (or expanded to include Air Traffic Control), it would be desirable to pattern it after existing systems to minimize the cost of development. For example, if JTIDS can't be used, it would be desirable to pattern the new system after JTIDS to take advantage of all the engineering that has already gone into JTIDS. In fact, in the following, suggestions are presented for a data link systems that are patterned after JTIDS, but has a reduced capacity, but improved LPI capability, for the purpose of reducing complexity and costs. They take advantage of another evolution of the JTIDS signal structure presented in Figure 3.

---

[9]The following appeared in the June 24, 1991 issue of *Aviation Week & Space Technology* Filter Center column: "NAVAL AIR DEVELOPMENT CENTER is seeking a low probability of intercept (LPI) voice/data communications system that will give aircraft a 200-mi. communication capability. Other desired functions are wingman to wingman communication, an LPI carrier aircraft inertial navigation system alignment and an LPI automatic carrier landing system. Ideally, the proposal would add a secure/LPI capability to existing UHF radios that would be compatible with Link 4 and the UHF radio form factors. Contact H. Jaffe, (215) 441-1512."

[10]Magnavox Government and Industrial Electronics Company data sheet and presentation. Contact is Ralph Schoolcraft, Program Manager, (213) 618-1200, Extension 3342.

These new data link systems are presented as either operating in the current JTIDS/TACAN frequency band (L-Band LPI data link) or as an LPI replacement for LINK-4A, but compatible with LINK-4A (LINK-4 LPI data link). As it turns out, it really doesn't matter which frequency band is used. The resulting signal structure and performance would be similar. The advantage of operating with LINK-4A is that the possibility of a data link being developed for that band is already being considered and it can be made to be backward compatible with the existing LINK-4A.

2.2.7.1 Evolution to a New Data Link in the JTIDS/TACAN Frequency Band (L-Band LPI Data Link) A modified signal structure that could be received and transmitted by modified existing JTIDS terminals was described above. Here, that will be extended to where if, in addition to those modifications, a complete new system were developed, although more extensive JTIDS terminal modifications could be made to still be compatible.

If interference to TACAN is not a concern in the future when it is replaced, then the JTIDS pulse width can be increased. This is accomplished by reducing the chip rate to 1 MHz, while increasing the pulse width by a factor of five. The wider pulse means that the receiver noise bandwidth is reduced by a factor of five, thus increasing sensitivity. It would also mean that the number of frequency hop bins could be increased by a factor of five to cover the same overall signal bandwidth with one-fifth the hop rate. The increased sensitivity means that the peak transmitter power can be further reduced from 40 watts (with the improved noise figure) to 8 watts, although the average transmitted power would stay the same. Reducing noise bandwidth also increases processing gain with a corresponding increase in AJ margin. The reduction in transmitter peak power by 7 dB does nothing to reduce the radiometric interceptor area of detection because the average power is not decreased. But the larger number of hop frequencies does improve the LPI capability against interceptors that are trying to detect at the hop frequencies, because the power transmitted at any one frequency is reduced by 7 dB. This technique also improves the AJ capability against CW or swept CW jammers significantly.

Figure 3 illustrates this total evolution of the JTIDS signal waveform to this LPI waveform. Part 1 and part 2 of this figure shows the evolution discussed above for the JTIDS terminal modification and the JTIDS Derivative terminal, where the existing JTIDS waveform is illustrated in part 1 with its 258 pulses in 3.354 milliseconds. Each pulse (or pulse pair) represents a 32 chip symbol, resulting in a very high data rate. Part 2 illustrates reducing that data rate so that the number of pulses can be reduced and randomized. By then increasing the pulse width, as illustrated in part 3, the receiver's noise bandwidth and the peak transmitted power can also be reduced.

The architecture of a terminal for this evolved L-Band LPI data link is identical to that of one that could operate in the LINK-4A frequency band, except for the fact that its front end is tuned to the L-Band frequencies instead of UHF. More transmitted power is required because of the higher frequencies, but the LPI characteristics would be the same, since the space loss to him is the same as to the user. Because of the similarity in architecture, the description of a terminal for this L-Band LPI data link is given below in the discussions of the LINK4-A LPI data link.

A specification for this proposed data link is provided in Appendix VI along with the specifications of all the other elements of the DGPS system.

2.2.7.2 Evolution to a New Data Link in the LINK-4A Frequency Band (LINK-4A LPI Data Link) The same type of signal structure can be applied to the LINK-4A frequency band (225-400 MHz), without interfering with the existing LINK-4A signals. The resulting terminals would still be capable of transmitting and receiving LINK-4A signals. Note that the frequency allocation of 175 MHz is close to that of JTIDS. Thus the radiometric interceptor's noise bandwidth is compatible with that for the JTIDS signals. An overall block diagram of a the terminal is shown in Figure 4. Note that the modulator and demodulator blocks include the Frequency-Shift-Keying (FSK) modulation and demodulation for the existing LINK-4A system. In that case, frequency hopping is inhibited, but assigned to the corresponding frequency channel. In the case of the new data link signal structure, channelization can be achieved by different PN sequences for the frequency hopping and symbol encoding.

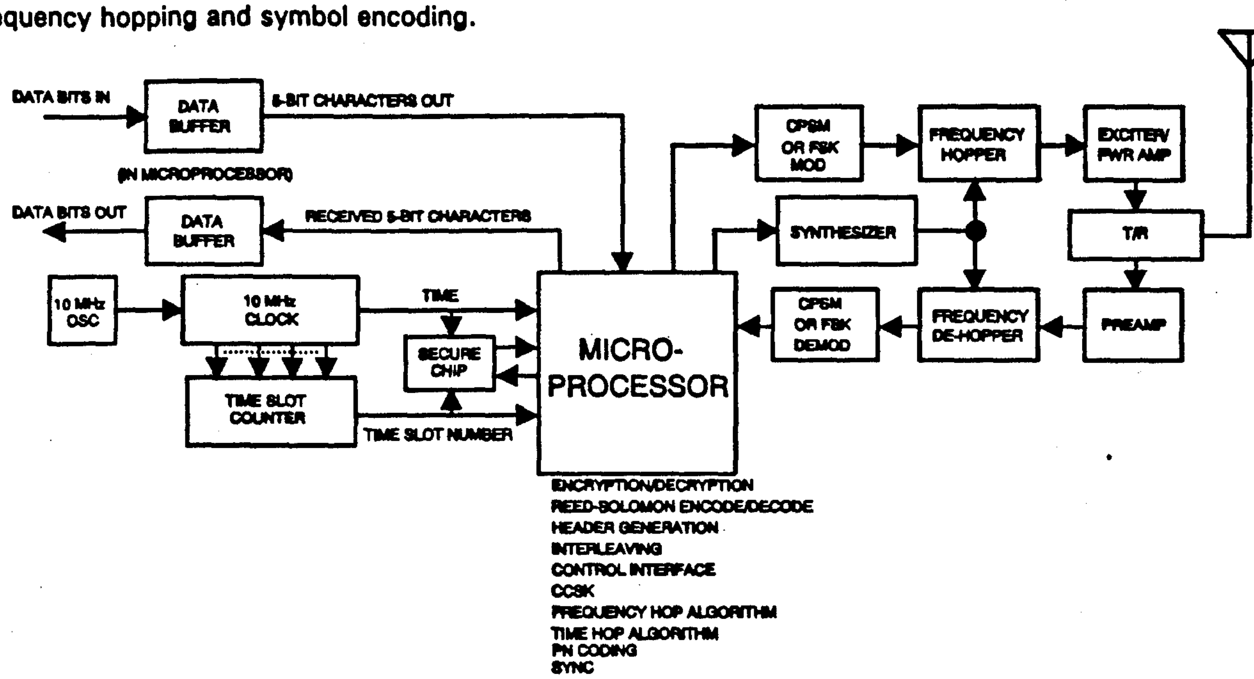

Figure 4. L-Band/LINK-4A LPI Data Link Terminal Block Diagram

The key features of this proposed LPI data link terminal illustrated in is that many of the functions performed in hardware in the JTIDS terminal can be performed in the Microprocessor, which is in the category of and Intel i860 embedded processor. Note the list of functions assigned to that processor below it in the figure. This list even includes the generation of the 1 MHz PN CCSK codes. This coupled with the low power output is key to realizing a cost effective terminal that meets the cost goals for the Shipboard TACAN Replacement using DGPS. Another important feature is that the time slot timing is tied to that of the LINK-4A data link, which is indicated in the data link specification. This is not a requirement for the system if operating at L-Band, but if the L-Band version did, it would be also be compatible with LINK-4A, since it wouldn't be compatible with JTIDS anyway.

Another key feature of this proposed LPI data link is related to the structure of the synchronization pulses. In the Modified JTIDS/JTIDS Derivative structure presented above, the use of fewer frequencies during the synchronization period was proposed to minimize the number of receivers required in the JTIDS Derivative terminal. In the case of this new link, however, we can go one step further. Without concern for TACAN the synchronization preamble can use two frequencies on alternate pulses. With two frequencies one can coherently integrate the pulses at the same frequency. This improves the integration gain to 3 dB for each doubling of the number of pulses. Five pulses then have an integration of 7 dB. Five per frequency plus the noncoherent combining of 2.2 dB on two frequencies provide an overall gain of 9.2 dB using only 10 pulses overall. This compares to 8.8 dB for 16 pulses of the current upper or lower antenna JTIDS design. In fact, seven or eight pulses at only one frequency randomly selected from the 175 (or 153, in the L-Band case) would essentially provide the same performance as JTIDS with fewer pulses. Thus, a terminal with only one receiver is certainly a possibility, further reducing cost (and size, weight and power).

A block diagram of the modulator/demodulator for this proposed terminal is shown in Figure 5. Note that the correlators are in software in the Microprocessor. Thus, the ability to coherently integrated before noncoherent detection requires no extra hardware.

A specification for this proposed data link appears in Appendix VI along with the specifications of all the other elements of the DGPS system.

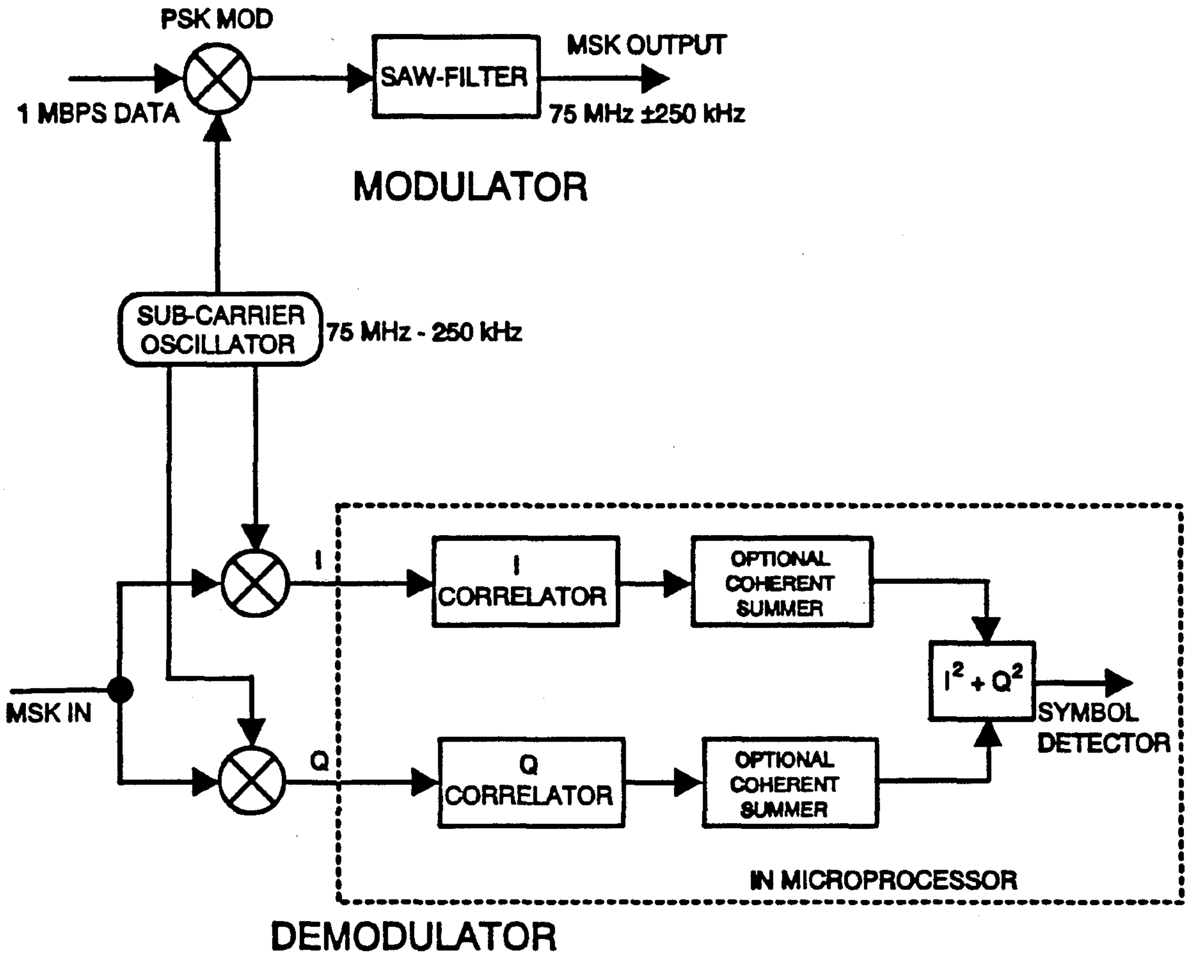

Figure 5. L-Band/LINK-4A LPI Data Link Terminal Modulator/Demodulator Block Diagram

2.2.7.3 L-Band/LINK-4A LPI Data Link Terminal Cost Reduction and LPI Improvement Factors Table I presents a summary of the L-Band/LINK-4A LPI data link terminal cost and LPI improvement parameters and rationale for the ability to reduce cost relative to that of JTIDS. In summary terms, these are

1) The elimination of the Round Trip Timing function by synchronizing the network and the terminals to GPS or UTC Time, thus eliminating a processor throughput burden.

2) Reducing the number of frequencies transmitted during the synchronization period, thus, reducing the number of terminal receivers required for synchronization,

3) Reducing the system noise figure of the terminal receiver, thus improving receiver sensitivity and reducing transmitter power, allowing for lower cost and more efficient transmitters as well as an improved LPI capability,

4) Transmitting only one Reed-Solomon word per time-slot, which reduces transmitter duty cycle and randomized the transmitted pulses, allowing for a lower cost transmitter and an improved LPI

capability,

5) Reduce the chipping rate to 1 MHz and increase the pulse width, thus reducing peak power and increasing AJ and LPI capability.

Table I. L-Band/LINK-4A LPI Data Link Terminal Cost and LPI Improvement Parameters

PARAMETER	RATIONALE
GPS Provides Net Time Reference	GPS (UTC) Time eliminates the need for the Round Trip Timing (RTT) function. Eliminating this function enables Reed-Solomon decoding to be done in software for the data Reed-Solomon code words.
More Synchronization Pulses on a Single Frequency	JTIDS now requires eight receivers to minimize interference to TACAN. The number of receivers are reduced if the number of frequencies are reduced for the synchronization preamble. Alternating two frequencies will reduce the number of receivers to two. Using a single frequency chosen at random will reduce the number of receivers to one. Also, consideration can be given to coherent frequency hopping for synchronization. The integration gain for synchronization is then increased, providing the same performance as before with fewer receivers.
Improved Receiver Sensitivity	Improved receiver sensitivity with a lower noise figure enables the terminal transmitter power to be reduced while realizing the same receiver performance.
Time-Hopping by Reducing the Number of Reed-Solomon Code Words in a Time Slot	Sending the header plus one Reed-Solomon code word appears as a time-hopped signal after interleaving. Capacity is reduced to 9600 bits per second and the duty cycle of the transmitter is also reduced.
Reduce PN Chipping Rate from 5 MHz to 1 MHz in Derived JTIDS or LINK-4A Terminal	Pulse width is increased from 6.4 μseconds to 32 μseconds. Processing gain is increased, receiver sensitivity is increased, frequency hopping rate is reduced, number of frequency hop bins is increased, multiple access is improved, transmitter peak power is reduced and AJ and LPI capabilities are improved.

2.2.8 <u>Investigation of Existing Data Links Summary</u> Table II summarizes the candidate data links, existing or otherwise, and compares them against the 10 requirements and desired capabilities specified in Section 2.1.4. Pseudolites, which are addressed later in this report, are also included. However, since they would only provide a one way link capability, they would not be acceptable for air traffic control applications. TADIL C, Link 4-A, TADIL A, Link-11, and TADIXS are not included as candidates for reasons given in Sections 2.2.1, 2.2.2, and 2.2.4. A modified JTIDS is included. The new data link indicated in *Aviation Week & Space Technology* is included as proposed LINK-4A LPI data link. The proposed L-Band LPI data link that would operate in the JTIDS/TACAN frequency band is lumped together with the proposed LINK-4A LPI data link. They both have the same characteristics. Either one is recommended.

Table II. Candidate Data Link Summary

REQUIREMENT OR DESIRED CAPABILITY	JTIDS	MILSTAR	MODIFIED JTIDS/JTIDS DERIVATIVE	LINK-4A/ L-BAND LPI LINK	PSEUDO-LITES
Accuracy	Yes	Yes	Yes	Yes	Yes
Low Probability of Intercept	No	Yes	Yes	Yes	Yes
Anti-Jam Margin	Yes	Yes	Yes	Yes	Some
EMI	Yes*	Yes	Yes*	Yes	With Limitations*
Data Encryption	Yes	Yes	Yes	Yes	Yes
Unlimited No. of Users**	Yes	Unknown	Yes	Yes	Yes
Air-to-Air Range & Bearing	Yes	Unknown	Yes	Yes	No
Meets Cost Goals	No	No	Maybe	Yes	Yes
Integrated Logistic Support	Yes	Unknown	Yes	Yes	Yes
ATC Enhancements***	Yes	Unknown	Yes	Yes	No

* JTIDS operates in band allocated to TACAN. JTIDS allocation is temporary, but if TACAN is phased out, this may not be a problem. Pseudolites potentially interfere with GPS signals.

** In a broadcast mode. However, with multiple networks (channels) and time slots, the number of users using two way communications is essentially unlimited.

*** Air Traffic Control would require transmission response from aircraft.

THIS PAGE INTENTIONALLY LEFT BLANK

2.3 DGPS Technique and DGPS Data Link Content

A preliminary DGPS concept for the Shipboard TACAN replacement is provided Appendix I as an excerpt from the ION GPS-90 paper. This concept does not include provisions for Air Traffic Control, but neither does TACAN without voice contact with a controller. The concept presented suggests the broadcast of the ships' locations as moving waypoints that would be accepted by the GPS receiver, a capability that currently exists in the Navy's GPS receivers, specifically the RCVR 3A and the Miniature Airborne GPS Receiver (MAGR). Our major considerations here are for the MAGR, since that is the receiver projected for the Navy's aircraft. Because of upgrades incorporated into the MAGR, its area navigation (RNAV) capabilities are quite different that the RCVR 3A's, as is its interfaces to the operator and data links with respect to RNAV. These differences are indicated below.

It is important to note here that specifying requirements for RNAV and Air Traffic Control are beyond the scope of this study. However, at the same time, it is important that these requirements are understood because both of these functions rely heavily on the information supplied via the DGPS data link. Thus, the following discussions step over the boundary into RNAV and Air Traffic Control, even to the degree of pointing out potential problems in the specified RNAV requirements.

It is also important to note that, in many of the existing aircraft into which GPS will be installed, the RNAV function will not reside in the GPS receiver, but in a mission computer. In this case, the mission computer will simply use the GPS navigation solution from the receiver as an input to the RNAV function, while using waypoints derived from the ship's GPS navigation solution to implement that function. However, the mission computer may still use the GPS receiver as a mechanism for storing waypoints and, possibly, computing RNAV parameters. Of course, the requirements that are derived during the course of this study will then apply to partially or totally the mission computer. However, this study will treat the subject as though it will be implemented in the MAGR, using information supplied to it via the 1553 bus. It is believed that at least some of the requirements will apply to the mission computer as part of the overall vehicle integration.

2.3.1 MAGR RNAV Requirements The MAGR RNAV requirements are specified in the MAGR development specification.[11] Paragraph 3.1.2.1.a of that specification states the requirement that "The MAGR's principal means for interfacing with the HV (Host Vehicle) will be its dual-redundant MIL-STD-1553 multiplex bus interface. This interface shall be used to:

aa. Control the operation and functioning of the MAGR.

bb. Receive data to facilitate GPS navigation solution initialization/aiding, receiver aiding, area navigation (RNAV) computations, SA/A-S, and instrumentation/maintenance functions.

cc. Provide in output messages, receiver/LRU status, initialization data, GPS PVT navigation solutions and related data, RNAV data, satellite almanac and ephemeris information, and instrumentation and maintenance information."

It is important to note that the MAGR development specification specifies no interface to a Control Display Unit (CDU), unlike the RCVR 3A. The control of the MAGR is performed via the 1553 bus, as indicated in aa. above. However, the inputs and outputs via the 1553 bus could very well be CDU inputs and outputs, since a CDU could either be on the same bus or interfaced to the mission computer that is on the same bus, depending upon the aircraft configuration. Also, another source, such as a data link, could emulate CDU inputs. Those inputs would probably also be routed through the mission computer. Thus, anywhere in the specification where the word "operator" appears, it is assumed that the "operator" could be a data link

---

[11] Specification for NAVSTAR Global Positioning System (GPS) Miniature Airborne GPS Receiver (MAGR), Final Draft, Specification Number CI-MAGR-300, Code Identification 07868, 30 March 1990.

providing a "remote" operator.

The MAGR specification Paragraph 3.2.1.3.24 then specifies Waypoint Navigation requirements. However, Appendix IV of that specification gives "Priced Option" requirements. Paragraph 40.2 specifies Navy requirements for the MAGR that completely replace Paragraph 3.2.1.3.24 with Area Navigation (RNAV) requirements. This "Priced Option" has been exercised, and the requirements in the appendix do indeed replace those in Paragraph 3.2.1.3.24. From here on, these requirements will be referred to as the new RNAV requirements.

These new RNAV requirements, which were derived by NADC, expand the capability of the MAGR significantly over that of the RCVR 3A. In summary, they increase the number of basic waypoints (sometimes called active, moving or flight plan waypoints), include the capability of inputting and storing flight profiles and inputting and storing flight plans. These new requirements will make it much easier to implement DGPS as a replacement to Shipboard TACAN. However, there still appears to be some minor problems that make the implementation somewhat awkward. A discussion of the requirements and how they apply to DGPS and a discussion of these minor problems follows.

The applicable 1553 bus interface is specified in the draft MAGR version of ICD-GPS-059[12], which is different than the RCVR 3A version.[13] This new draft version of ICD-GPS-059 basically describes the implementation of the new RNAV requirements.

2.3.1.1 RNAV Functions The MAGR specification specifies three basic RNAV functions:

1) Lateral Navigation,

2) Enroute/Terminal Area Operations,

3) Rendezvous Operations.

All of these functions apply to the DGPS replacement to Shipboard TACAN. They can all be performed using moving waypoints.

2.3.1.1.1 Lateral Navigation Requirements The Lateral Navigation requirements are simply the basic requirements for the computation of the following Lateral Guidance data:

1) Desired Track,

2) Track-Angle Error,

3) Cross-Track Error,

4) Bearing-To Waypoint,

5) Distance-To-Go,

---

[12]<u>NAVSTAR GPS Phase III Interface Control Document, GPS User Equipment - MIL-STD-1553 Multiplex Bus Interface</u>, ICD-GPS-059, Revision B, IRNs 001, 003 and 004, Draft MAGR Version, 14 June 1991. This draft MAGR version defines the CI-MAGR-300 RNAV requirements implementation as of that date.

[13]<u>NAVSTAR GPS Phase III Interface Control Document, GPS User Equipment - MIL-STD-1553 Multiplex Bus Interface</u>, ICD-GPS-059, Revision B, GPS-89-11132-025, IRN 001, IRN-004, 8 May 1990.

6) Along-Track Distance.

7) Time-To-Go.

This data shall be computed based on a computed "Course", which is the shortest great circle path between two waypoints, which could be moving waypoints. In fact, one of the waypoints could be the UE computed position. A description of all of these terms and how they are computed in the MAGR appears in a PLANS '90 paper written by Rockwell International.[14] Care must be taken in reference to that paper, however, as it was a proposed implementation of RNAV. It does not always reflect the new RNAV requirements. This Lateral Guidance data satisfies the requirements implied by a Navy GPS/CV Phase II User Equipment DT&E report.[15]

2.3.1.1.2 Enroute/Terminal Area Operations In addition to the Lateral Navigation requirements, the MAGR shall allow a holding pattern to be established at any waypoint including moving waypoints, and provide a "direct-to" function to define a route segment from the present position to any waypoint in the flight plan or to any waypoint in the data base. The holding pattern appears to be equivalent to "marshalling" points as defined in the Phase II DT&E document. The "direct-to" capability of the MAGR is described in the Moen and Bartholomew paper.

Both of these capabilities apply to the Shipboard TACAN replacement using DGPS in that the holding pattern waypoints can be defined with respect to the GPS position and velocity of the ship, including glide path information defined by the "Desired Altitude" at the reference point (moving waypoint defining the ships location) and the "Initiating Altitude" and "Distance From the Reference Waypoint" associated with the moving waypoint. "Initiating Altitude" doesn't appear to be a capability of the existing waypoint definitions in ICD-GPS-059, unless it is interpreted as being defined from the "desired vertical angle", "offset range" and "offset bearing" parameters in the I-4 Waypoint Definition message. However, this has nothing to do with the capability to do DGPS.

2.3.1.1.3 Rendezvous Operations If the flight plan contains a moving waypoint, it is considered a "rendezvous operation". The MAGR shall compute an intercept or point of closest approach with that waypoint, and the navigation solution shall indicate a great circle route to that intercept. A moving waypoint is a "Basic Waypoint" with a position fix, ground track, and ground speed; if the time of the position fix is different from present time, the operator must enter the time of the fix. The fix time shall be in Coordinated Universal Time (UTC). Upon entry of essential data, the MAGR shall calculate the time-to-rendezvous and the bearing from the vehicle to the waypoint (not the intercept) (and) desired track to the intercept point (not the waypoint). The present position of a moving waypoint and the position of intercept shall be displayable.

If a rendezvous is not possible or if it becomes not possible, the MAGR shall calculate the point of closest approach to the target trajectory (missed distance) and shall indicate in a status word a "No Rendezvous Possible" condition. The position of rendezvous will be periodically recomputed based on progress toward the intercept.

These requirements imply that an operator must select the moving waypoint from the stored "Basic Way-

[14]Verlyn Moen and Redge Bartholomew, "Area Navigation Capability in a Miniature Airborne GPS Receiver", Record of the IEEE 1990 Position Location and Navigation Symposium (PLANS), Las Vegas, Nevada, 21-23 March 1990.

[15]Vectored Waypoint Analysis Objectives and Approach, prepared for the Naval Air Development Center Communication Navigation Technology Directorate, Code 401, by Intermetrics, Inc., Warminster, PA, 1 March 1983.

points", which only he has control over. However, since the operator of the MAGR interfaces to it via the 1553 bus, the MAGR can't tell from where the selection is coming. Thus, the entry <u>and</u> the selection of a moving waypoint can be accomplished via a data link and/or the mission computer connected to the 1553 bus.

The time of fix is indicated as "Starting Time" in the I-4 Waypoint Definition Message.

Note that the desired track computed is that to the intercept point, which is, of course, the position of the waypoint at the time of intercept. This is inconsistent with another definition in the literature that states that the desired course is set to the ground track of the moving waypoint.[16] This has been confirmed by Rockwell and indicated that both modes of rendezvous are being implemented. Yet, there are phases of flight, such as Nonprecision or Precision Approach, where the desired track is that which lines the aircraft up with a Carrier Vehicle runway that is not necessarily along either one of those desired courses. Sometimes this is neither of the above definitions. These definitions are illustrated in Figure 6. One is the great circle route to the point of intercept, one has the desired track being the ground track of the carrier, and one has the desired track being the bearing of the runway. Note the difference in desired tracks for each of the three definitions. Clarification of this requirement is in order. Of course, a flight plan (described below) could be set up such that the preceding ("FROM") waypoint was a moving waypoint that was lined up with the runway and moving with the runway, but at a distance projected from the end of the runway. Then, once the host vehicle changes legs at that preceding waypoint, the great circle route to the intercept is lined up with the runway. This is essentially the concept described in Figure I.2 of Appendix I.

It is inconceivable that rendezvous with a ship would be impossible. Thus, requirements with respect to impossible rendezvous does not apply to the Shipboard TACAN replacement application.

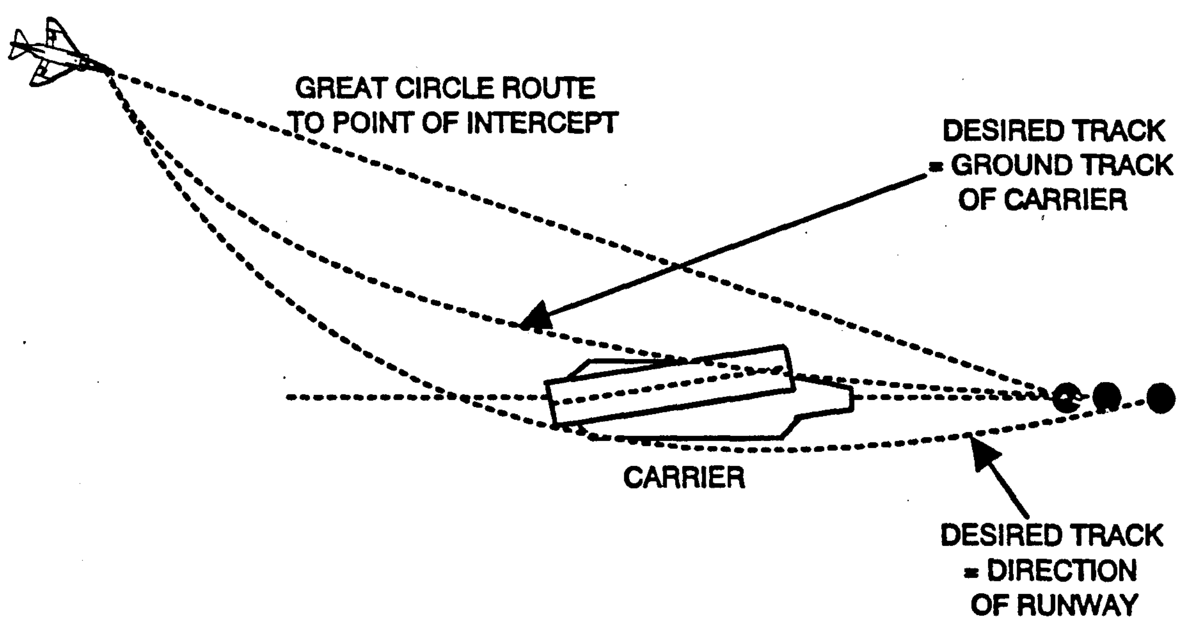

Figure 6. Three Desired Tracks to Point of Intercept

[16]G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, 21-25 September 1987.

Also, Private Communication with Redge Bartholomew of Rockwell International.

2.3.1.2 Navigation Data Base The MAGR specification defines the navigation data base. The MAGR shall maintain a navigation data base comprised of geographically locatable waypoints, flight profiles, flight plans and magnetic variation data. This data base shall constitute the stored information which the MAGR shall use to perform the RNAV computations. The navigation data base shall contained a non-editable (fixed) portion comprised of downloaded waypoints and flight profiles, and an operational (working) portion comprised of the basic waypoints and the flight plans. The non-editable data base (NEDB) shall be loaded only from a 1553 data loader, while the operational data base (ODB) may be obtained either by manual entry or by editing data copied from the NEDB.

From these requirements it is obvious that DGPS operation must be accomplished via the ODB using basic waypoints and flight plans, but not by editing data copied from the NEDB. Again, manual entry would be via the 1553 bus, which could just as well be from a data link. Thus, in general, requirements for DGPS operation are met, except for minor problems associated with writing over existing waypoints. That problem will be discussed later.

2.3.1.2.1 Waypoints The MAGR specification defines two different types of waypoints -- downloaded waypoints (200) and basic waypoints (24). Downloaded waypoints are those received via the 1553 bus from a data loader. This implies that the MAGR won't expect them in real-time. They are stored in non-volatile memory and are part of the MAGR navigation data base that is non-editable (NEDB). They do not include any moving waypoints. Thus, the downloaded waypoints cannot be used for DGPS for Shipboard TACAN Replacement, although they certainly can be used for the general case of DGPS which includes navigating with respect to fixed TACAN stations.

Basic waypoints, on the other hand, are stated to be strictly operator-entered. However, since an operator can only enter them via the 1553 bus, the MAGR can't tell if they are entered by an operator or a data link. In the case of the data link, the operator is remote. These basic waypoints are part of the operational navigation data base and are editable (ODB). The specification states the following:

> "... Basic waypoints shall be created by a new 1553 data block entry or geographic data, by making a copy of a downloaded waypoint, or by designating an offset from an existing geographically-defined waypoint. Basic waypoints may be either stationary or moving, and if moving, shall require an associated ground speed, ground track and time-of-fix, in addition to starting position coordinates. The present position coordinates of a moving waypoint shall be kept current. ... A basic waypoint shall be distinct from the identifiers used for downloaded waypoints and profiles. The MAGR shall permit the operator to scan the list of Basic waypoints for selection and use. Basic waypoints shall be capable of being defined relative to either another "Basic" or "Downloaded" waypoint for the establishment of offset waypoints or glide path initialization. ..."
>
> "Basic waypoints shall contain the Waypoint Identifier, 3-Dimensional Position, Geographic Datum of the cited position, Magnetic Variation at the way-point, Slaved Variation of the waypoint (if applicable), Ground Speed, Ground Track (true), Time of Fix (UTC), Reference Waypoint Identifier, Desired Bearing (true) and Radial Bearing (Computed with slaved variation) from the Reference Waypoint, Initiating Altitude, Flags and Status. Ground Speed, Ground Track, and Time of Fix are associated with moving waypoints; Desired Altitude and Initiating Altitude are associated with establishing a waypoint at the start of a glide path; and Reference Waypoint and Distance from the Reference Waypoint can be associated with either offset or glide path initialization waypoints."

Basic waypoints (moving) meet the requirements for use with DGPS for Shipboard TACAN replacement.

2.3.1.2.2 Flight Profiles The MAGR specification defines a flight profile as a stored group of preplaned waypoints. They are loaded only with a data loader and are located in the NEDB. Thus, they don't include any moving waypoints and cannot be used for DGPS for Shipboard TACAN replacement.

2.3.1.2.3 Flight Plans The MAGR specification makes provisions for flight plans. The MAGR shall provide for the definition of two flight plans: an active flight plan and an alternate. Each plan consists of a series of geographically locatable waypoints, which may be entered as downloaded waypoints, basic waypoints, or flight profiles. Great circle paths shall be automatically computed between each pair of waypoints.

Flight plans are very applicable to Shipboard TACAN replacement using DGPS because they can be updated in real-time and can use basic waypoints. The concept of using DGPS for the Shipboard TACAN replacement is to use real-time uploaded moving waypoints.

The MAGR specification continues to refer to "operator" definition and selection. Again, for the purpose of DGPS operations, "operator" is assumed to include definition and selection via a data link, since, in the MAGR, all control of the operation and functioning is performed via the 1553 bus. Some of the "operator" capabilities with respect to flight plans, as they relate to DGPS, specified are as follows:

1) Select any basic waypoint by entering its alphanumeric identifier frequency or channel, as applicable.

2) Establish a direct course ("direct-to") to any waypoint in the data base, or to a waypoint in the flight plan.

3) Establish a Holding Pattern at a waypoint ("Datum").

4) Establish a rendezvous with a moving waypoint. The MAGR shall create a temporary waypoint that represents the intercept on its own vehicle's track with that of the moving waypoint and follow a great circle route to the intercept.

5) Delete any waypoint from a flight plan.

Item 1 is important in that the MAGR, based upon a transmitted flight plan or destination designation (as defined in ICD-GPS-059), must be able to select waypoints based on its identifier, rather that its waypoint number (as defined in ICD-GPS-059), since a waypoint number may be ambiguous. Also, as illustrated in Figure 1 above, Item 4 creates a slight problem in that the "desired" vehicle's track to an aircraft carrier may be the direction of its runway, and not the track to the intercept point. But, as described above, that problem can be overcome with a flight plan that defines a "preceding" waypoint that is a moving waypoint projected along a line along the runway.

2.3.1.3 RNAV Requirements Summary In general, the MAGR's requirements for rendezvous operations using moving waypoints meets the requirements for the proposed DGPS technique. Twenty four moving waypoints, or a flight plan made up of up to 24 moving waypoints can be input to the MAGR via the 1553 bus in real time to be used for RNAV functions. These waypoints can all be relative to a ship. These waypoints and flight plans can be used in a "differenced" DGPS mode to emulate the functions of Shipboard TACAN and much more.

2.3.2 DGPS Data Link Message Content As a minimum, the DGPS data link message content is required to consist of waypoints and flight plans. It should also contain information such as aircraft tail number or some other aircraft identification to direct messages as appropriate.[17] The message content for the waypoints and flight plans should at least consist of the data required for the MAGR 1553 bus interface mes-

[17] Vectored Waypoint Analysis Objectives and Approach, prepared for the Naval Air-Development Center Communication Navigation Technology Directorate, Code 401, by Intermetrics, Inc., Warminster, PA, 1 March 1983.

sages, although, some of the data may be generated by the aircraft's mission computer on the way to MAGR. The 1553 bus interface to the MAGR is specified in a new version of ICD-GPS-059.[18] Input messages I-3 (Destination Designation), I-4 (Waypoint Definition) and I-25 (Flight Plan Definition) and output messages G-3 (Destination Data), G-4 (Waypoint Data), G-25 (Flight Plan/Profile) and G-26 (RNAV Status) apply to the input and output and the use of basic waypoints and flight plans. In addition, for the purpose of position reporting, the output message G-9 (Background Navigation Data) applies.

2.3.2.1 1553 Bus Interface Description Appendix IV is a summary description of the information provided in ICD-GPS-059, related to the handling of inputs of waypoint and flight plan information and providing steering information, range to destination and time-to-go to destination and position and velocity information to the 1553 bus.

2.3.2.1.1 1553 Bus Interface Summary The 1553 bus interface as described in MAGR version of the ICD-GPS-059 meets the requirements for the proposed DGPS technique. Although a protocol must be set up in the host vehicle's mission computer, the messages are available at the 1553 bus interface to control the MAGR to perform the Shipboard TACAN replacement using DGPS. The messages are also available to perform a guided RNAV function using moving waypoints. At a top level, the procedure for causing the MAGR to perform these functions is as follows:

1) Send I-4 Waypoint Definition messages entering moving waypoints describing a desired flight plan into the MAGR's Basic Waypoint data base.

2) Send I-25 Flight Plan Definition messages describing the sequential use of those entered waypoints.

3) Send I-3 Destination Designation message(s) to start the use of the flight plan.

4) The flight plan can be updated dynamically at any time by sending additional waypoints and deleting and adding waypoints to the flight plan, including holding fix waypoints.

The MAGR computes steering information based on its RNAV computations using the waypoints and flight plan. It outputs that information back to the mission computer via the 1553 bus via the G-3 Destination Data Output Message. If the host vehicle has the flight instruments connected to the MAGR via the ARINC 429 interface, the MAGR will output the steering information directly to the flight instruments. The MAGR also outputs all the data it received so correct reception can be verified.

2.3.2.2 Data Link Message Content In order to accommodate RNAV and air traffic control requirements, it will be necessary to have data link messages in two directions. Without getting into the details of those subjects, which is out of the scope of this study, only an overview of the data message content will be presented.

2.3.2.2.1 Data Link Message Content Transmitted to the Host Vehicle In order to be compatible with the 1553 bus message structure, it makes sense to have the incoming data link message content contain the information that is required to build the 1553 bus I-3, I-4 and I-25 input messages. The message should also contain a header defining the aircraft tail number[19] and message ID. This is because an air traffic

---

[18]NAVSTAR GPS Phase III Interface Control Document, GPS User Equipment - MIL-STD-1553 Multiplex Bus Interface, ICD-GPS-059, Revision B, IRNs 001, 003 and 004, Draft MAGR Version, 14 June 1991. This draft MAGR version defines the CI-MAGR-300 RNAV requirements implementation as of that date.

[19]Vectored Waypoint Analysis Objectives and Approach, prepared for the Naval Air Development Center Communication Navigation Technology Directorate, Code 401, by Intermetrics, Inc., Warminster, PA, 1 March 1983.

controller would not necessarily be directing all host vehicles to the same waypoints. There are cases where he might, such as a marshalling point, so a general identification might be used for broadcast type messages. As discussed above, not all the data in those 1553 bus messages have to be sent, since some of it doesn't apply to the application of DGPS, which would use the only Basic Waypoints in an automatic sequencing flight plan mode. Some other content, such as waypoint number, etc., would not be appropriate for data link messages, and should be added by the mission computer. This would be part of the protocol between the mission computer and the MAGR.

2.3.2.2.2 Data Link Message Content Transmitted by the Host Vehicle Return messages with selected content of the G-3, G-4, G-9, G-25 and G-26 1553 bus output messages would be appropriate as return verification and position reporting messages, if a two-way capability existed in the data link. These messages should also have a header with aircraft tail number and message ID. It is not likely that a data link used for air traffic control would not have a return response capability for verification. Selected content from these 1553 bus messages is also required by the mission computer for establishing protocol between it and the MAGR.

2.3.2.3 Mission Computer Requirements The mission computer must intercept the messages in either direction. It is unreasonable to place the requirement on the DGPS control or air traffic controller to control the operation of the MAGR in each host vehicle. This control should be limited to defining waypoints and real-time flight plans for each host vehicle. Using this information, it is the mission computers requirement to provide control of the MAGR and to manage the MAGR's waypoint and flight plan data base. This includes defining waypoint numbers used in the I-4 Waypoint Definition input messages and controlling the insertion of new waypoints into a currently used flight plan. In addition, the mission computer should insert other pertinent data into the 1553 bus input messages that is not required from the data link source and strip data from the 1553 bus output messages not required by the data link source. These requirements are in addition to those for flight instrument and CDU display, if the mission computer is controlling the host vehicle elements.

The required message content of the 1553 bus messages adds up to a maximum bit count of about 450 bits of data for any one message. This does not include headers, parity, etc. This may exceed the single message capacity of the candidate data links that have good LPI capabilities. For example, in the case of the JTIDS message structures, this exceeds the capability of all the more robust message structures, which have a maximum capability of 408 bits, when accounting for all the parity and error correction bits. This would be one reason for eliminating some of the unnecessary data, and have the mission computer insert it for transmission to the MAGR via the 1553 bus. This becomes even more of an issue if the LPI capability of JTIDS is improved using lower data rates. Thus, the mission computer also inherits the requirement to build 1553 bus input messages from the bridging of multiple data link messages. The reverse is also true. The mission computer must also split up 1553 output messages into multiple data link messages for transmission. Thus, the mission computer must also control the data link's transmission.

The data rate requirements for DGPS should never exceed 500 bits per second, since the rapid update of waypoints and flight plans should never be required. Furthermore, the MAGR cannot handle the data much faster than that anyway. This is consistent with enhance LPI capabilities requiring relatively low data rates.

2.3.3 Shipboard RCVR 3S Output Requirements ICD-GPS-176[20] describes the data outputs of the Shipboard RCVR 3S to the Shipboard External Computer that would be used to generate the message content described above.

The RCVR 3S does not derive waypoint information for external use, nor should it. Waypoint information

---

[20]ICD-GPS-176, Revision A, Shipboard External Computer (MIL-STD-1397A) Interface, 30 April 1986.

should be derived by a Shipboard External Computer programmed as the Shipboard TACAN replacement, based on GPS information provided it by the RCVR 3S. In general, this information is the current GPS position and velocity of the ship, plus data required for enhancements described above in Section 2.3.2.2.1.

The RCVR 3S's interface with the Shipboard External Computer (EC) as specified in ICD-GPS-176 is relatively simple and does not transmit an abundance of data. However, the data flow is sufficient to support the Shipboard TACAN replacement using DGPS. The EC refers to one of the following systems, depending upon installation:

1) Inertial Navigation Set (AN/WSN-5),

2) Aircraft Carrier Navigation System (CVNS),

3) Electrically Suspended Gyro Navigator (ESGN),

4) Precise Integrated Navigation System (PINS),

5) Combat Direction System (CDS).

Note that at least 4 of the 5 systems are inertial navigation systems (INSs). Although the RCVR 3S interfaces with these systems via a MIL-STD-1397A parallel digital link, which is an NTDS (Naval Tactical Data System) type of interface, it is not an NTDS data link. That data link would be connected to the INS. In other words, ship installations apparently treat GPS as an aid to the INS, and the aided INS is the master navigator. But, that really doesn't make any difference to its application to the Shipboard TACAN replacement using DGPS. The output navigation solution from the INS is still a GPS solution, except that it is probably an INS smoothed version. That is probably the only solution that is available. It is assumed that this solution is based on the GPS navigation solutions provided to the INS (or EC), which are output by the RCVR 3S. These outputs are as follows:

1) Latitude,

2) Longitude,

3) North Position Variance,

4) East Position Variance,

5) North/East Position Cross Covariance,

6) Vertical Position with respect to the WGS-84 reference ellipsoid,

7) Vertical Position Variance,

8) East Velocity,

9) North Velocity,

10) East Velocity Variance,

11) North Velocity Variance,

12) North/East Velocity Cross Covariance,

13) Vertical Velocity,

14) Vertical Velocity Variance,

15) UTC Time-of-Day of Applicability,

16) Status.

Upon initialization of the RCVR 3S, the EC provides lever arms to the RCVR 3S. Then, in real time, the EC provides the ship's attitude (roll, pitch and heading angles). Thus, the RCVR 3S can and does make lever arm corrections to the ship's reference point.[21]

Note that the information required for the accuracy enhanced mode of DGPS is not available via to the EC -- namely, the PRN numbers of the satellites used in the RCVR 3S GPS navigation solution. This information would have to be added to this interface if that enhancement is desired.

This information is, however, available via the RCVR 3S instrumentation port (RS-422), as is all the information available to the EC.[22] Use of the RS-422 instrumentation port to bypass the EC is a definite alternative for the implementation of Shipboard TACAN replacement using DGPS.

2.3.4 Shipboard Use of DGPS The RCVR 3S has the capability to do waypoint navigation.[23] Unfortunately, that capability is only available via the CDU interface of the RCVR 3S. The interface with the EC does not provide that capability. However, that doesn't mean that some day it could not provide that capability, and thus, provide a DGPS capability relative to other ships.

---

[21] Prime Item Development Specification for the R-2331/URN Radio Receiver fo the User System Segment Navstar Global Positioning System, Specification Number CI-RCVR-3011A, Code Ident 13499, 21 March 1988.

[22] G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

[23] G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

2.4 Derivation of Pseudolite Signal Structure

A pseudolite (PL) is a one-way data link in the form of a shipboard transmitter that transmits a GPS-like signal with a signal structure that is compatible with the GPS satellite signals at one or both of the GPS frequencies. These signals can also serve as ranging signals. In Appendix III, the application of Shipboard TACAN Replacement requirements to pseudolites are addressed to point out the advantages and disadvantages of such an application, and a PL signal structure is derived.[24]

2.4.1 Advantages of Pseudolites The major advantage of using pseudolites as a DGPS data link is the capability to receive DGPS data in the MAGR without requiring an external data link. The benefits of this are reduced cost, size and weight, plus the elimination of installation requirements, which also reduces cost. The cost of shipboard installation of pseudolites is expected to be moderate and well within the goals specified in the TOR. The cost of modifying MAGR software to process the pseudolite signals will be an insignificant non-recurring cost when compared to the goals of the TOR.

Another advantage of using pseudolites is that they provide ranging signals from the ships that can be used to augment the RNAV capabilities as well as provide closing rate information. These features may be useful for an automatic landing system.

The signal structure derived in Appendix V also provides a limited LPI capability.

2.4.2 Disadvantages of Pseudolites The major supposed disadvantage of using pseudolites has been thought to be the interference cause because of the near-far problem. However, a pseudolite signal structure is derived in Appendix VII that dispels this supposition, at least with respect to their effect on the MAGR receiver. Their signals would have an interference effect on the older RCVR 3A and RCVR 3S designs. That effect is also moderate and well within the interference rules specified for those receivers. As part of the shipboard installation, the RCVR 3S antenna electronics can also be modified to accept blanking signals that would eliminate the interference to the RCVR 3S. Thus, this supposed major disadvantage should be down-graded to a minor disadvantage.

However, there are other disadvantages to using pseudolites. First of all, they would only provide a one-way data link. In the review of the RNAV and flight safety requirements reported on in previous and subsequent sections of this report, it is becoming obvious that a two way data link is required, if not for DGPS, but for air traffic control and flight safety reasons.

The second disadvantage is that tracking the pseudolite signal in the MAGR would require that one channel in the receiver be dedicated to the pseudolite. It is true that the MAGR has five channels, and it needs only track four GPS satellites to perform its navigation function.[25] However, it uses the fifth channel to acquire or reacquire satellite signals and to perform ionospheric delay corrections.

---

[24]This subject was addressed in the paper "Concepts for Replacing Shipboard TACAN with Differential GPS" by A. J. Van Dierendonck, Proceedings of ION GPS-90, the ION Satellite Division 3rd International Technical Meeting, Colorado Springs, CO, 17-21 September 1990. However, this report addresses this subject in more detail and consists of changes based on information not known when that paper was written.

[25]The MAGR actually has six physical channels. However, the sixth channel does not have the P code encryption capability, nor is the sixth channel serviced by the software. The software upgrade would be minor compared to the software required to accommodate pseudolite signals. However, to add the encryption capability would require the addition of an Auxiliary Output Chip (AOC), requiring a hardware modification of one of its boards.

A third disadvantage is that, using the normal 50 bit per second GPS data rate, the data rates achieved using pseudolite signals is marginal. However, these rates can be increased upward to 500 bits per second with software modifications in the MAGR. Increasing the bit rate by 10 increases the signal strength requirement by 10 dB. This should not be a problem, since there is almost that much margin anyway in the GPS signals for reliable data reception. However, software modifications would be required.

A fourth disadvantage is the fact that the LPI capability using pseudolites is marginal because the peak transmitted power has to be increased because of the low duty cycle. The low duty cycle is necessary to prevent interference to the GPS satellite signals. This would be alright if the MAGR could take advantage of the pulses and blank out noise and interference between the pulses. The pulse occurrence is pseudorandom and tied to the P-code state, which is available in the MAGR signal processing chips. However, those chips would have to be modified to perform this blanking function and all MAGR receivers would have to be retrofitted with new chips (3 in each MAGR). If that were accomplished, the LPI capability of pseudolites would be very good.

A potential disadvantage is that the location of the GPS antenna on the aircraft may degrade the reception of pseudolite signals to where it may be unreliable, primarily due to multipath. The degradation of received signal strength would not itself be a problem, since the pseudolite transmitting power could always be increased to compensate for that loss. One could postulate that another antenna could be added. This is how they solve the problem in the JTIDS system, and is a technique that has been used on other GPS applications where pseudolites have been used. However, the MAGR is not designed to accommodate more than one antenna. It would be a major modification to provide that capability.

2.4.3 Recommendations Regarding Pseudolites Based upon the weighing of the advantages and disadvantages of using pseudolites, their use is not recommended. This is primarily because they would only provide a one-way data link. Although DGPS by itself would be satisfied with this restriction, RNAV and flight safety requirements would not be met.

2.5 Review of Existing User Equipment Requirements Specifications

This task consists of reviewing exiting User Equipment (UE) specifications and interface control documents (ICDs) to determine the UE capability to operate in a DGPS environment and/or with pseudolites, and to determine what changes to the UE are required to operate in that environment and/or with pseudolites. The goal is to minimize changes.

2.5.1 Documents Reviewed The requirements documents reviewed specifically for this task or for Tasks 3 (Derive DGPS Technique and DGPS Data Link Content), 4 (Derive Pseudolite Signal Structure), 8 (Derivation of CDU Entry and Display Requirements), 9 (Derivation of Flight Instrument Interface Requirements) and 11 (Derive DGPS UE Requirements) are as follows:

1) Requirements specification for the Miniature Airborne GPS Receiver (MAGR)[26],

2) RCVR 3A software requirements specifications[27],

3) RCVR 3A and MAGR antenna electronics development specifications[28],

4) FRPA3 antenna development specification[29],

5) 1553 bus ICD for the MAGR[30],

6) ARINC 429 ICD[31].

The specifications reviewed are all requirements specifications that don't necessary contain the design detail required for the subject analysis. In fact, the information required for this study would probably only

---

[26]Specification for NAVSTAR Global Positioning System (GPS) Miniature Airborne GPS Receiver (MAGR), Final Draft, Specification Number CI-MAGR-300, Code Identification 07868, 30 March 1990.

[27]Computer Program Development Specification for the Receiver Pre-Processor CPCI of the User Segment User Equipment NAVSTAR Global Positioning System, Specification Number CP-RPP-2516. Code Identification 13499, 31 July 1981.

Computer Program Development Specification for the GPS Receiver/Processor CPCI of the User Segment User Equipment NAVSTAR Global Positioning System, Specification Number CP-RCVR-25X2.

[28]Prime Item Development Specification for the AM-7134/URN Antenna Electronics Amplifier of the User Segment NAVSTAR Global Positioning System, CI-AE-3061A, 21 March 1988.

Prime Item Development Specification for the AS-3820/AR Antenna Electronics 1 (AE-1) of the User System Segment NAVSTAR Global Positioning System, CI-AE-3060A, 9 November 1987.

[29]Critical Item Development Specification for the AS-3822/URN Fixed Reception Pattern Antenna 3 FRPA3 of the User Segment NAVSTAR Global Positioning System, CI-FRPA-3070A, 11 November 1987.

[30]NAVSTAR GPS Phase III Interface Control Document, GPS User Equipment - MIL-STD-1553 Multiplex Bus Interface, ICD-GPS-059, Revision B, IRNs 001, 003 and 004, Draft MAGR Version, 14 June 1991. This draft MAGR version defines the CI-MAGR-300 RNAV requirements implementation as of that date.

[31]GPS User Equipment -- Digital Flight Instruments (ARINC 429) Interface, Revision A, NAVSTAR GPS Phase III Interface Control Document ICD-GPS-073, 31 March 1986.

exist in government documents in the form of circuit diagrams and software code. It is not reasonable to obtain information from those sources. It is not even be reasonable to obtain those sources. However, there does exist a set of documents that is more descriptive of the UE implementation, although not official documentation. These are published papers written by the designers of the UE. These papers are on the following subjects:

1) Descriptions to the RCVR 3M (MAGR)[32],

2) Descriptions of the RCVR 3A and RCVR 3S[33],

3) Features and capabilities of the RCVR 3A and RCVR 3S[34],

4) A description of the area navigation capability of the MAGR[35],

5) A description of the RCVR 3A and RCVR 3S receiver processing algorithms[36],

6) A description of the RCVR 3A and RCVR 3S software[37].

---

[32]David E. Gray and Daniel C. Forseth, "Rockwell International's Miniature High Performance GPS Receiver", Proceedings of ION GPS-89, The Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, CO, September 27-29, 1989.

G. B. Frank and M. D. Yakos, "Collins Next Generation Digital GPS Receiver", Record of PLANS '90, IEEE Position Location and Navigation Symposium, Las Vegas, NV, March 20-23, 1990.

[33]John W. Murphy and Michael D. Yakos, "Collins Avionics NAVSTAR GPS Advanced Digital Receiver", Proceedings of the Institute of Navigation National Aerospace Meeting, Arlington, VA, March 22-25, 1983.

J. F. Vacherlon, et al, "GPS Phase III Multi-Channel User Equipment", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

[34]G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

[35]Verlyn Moen and Redge Bartholomew, "Area Navigation Capability in a Miniature Airborne GPS Receiver", Record of the IEEE 1990 Position, Location and Navigation Symposium - PLANS 90, Las Vegas, Nevada, 21-23 March 1990.

[36]Jeffrey C. Rambo, "Receiver Processing Software Design of the Rockwell International DoD Standard GPS Receiver", Proceedings of ION GPS-89, The Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, CO, September 27-29, 1989.

[37]R. G. Bartholomew, et al, "Software Architecture of the Family of DoD Standard GPS Receivers", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

The following two documents are not published papers, but are other sources of information helpful to the completion of this study.

1) A vectored waypoint analysis report published by Intermetrics, Inc. for NADC[38]

2) A data sheet for the FRPA3 antenna.[39]

2.5.2 Documents Not Reviewed In the proposal for this study and the task description in the contract for Task 8 this study (Derivation of CDU Entry and Display Requirements), documents pertaining to Control Display Units (CDUs) were to be reviewed. These are development and product specifications for the CDUs themselves. However, per guidance provided by the Navy, that interface does not exist in the Navy GPS UE. The Navy version of the GPS UE does not interface with CDUs directly, but via the 1553 bus. Thus, documents pertaining to CDUs were not reviewed.

2.5.3 Results of UE Requirements Review The documents listed above were reviewed to obtain specific information about the UE needed to perform this study to determine how the UE would operate with DGPS as a replacement for Shipboard TACAN. They were also reviewed to determine what changes might be required to the UE to operate with DGPS as a replacement for Shipboard TACAN. The following is a summary of the information obtained from those documents for those purposes.

2.5.3.1 MAGR Requirements Specification The MAGR requirements specification was reviewed to determine the MAGR's requirements for inputting and handling moving waypoints for the performance of Task 3 - Derive DGPS Technique and DGPS Data Link Content. The results of that review are documented as part of the documentation of the results of Task 3. Changes may be required of the MAGR software for handling moving waypoint updates. The details of these changes are still to be determined.

Appendix 4 of the MAGR specification specified "Priced Options" describing tailored changes to the main specification. Section 40.2 specified the option to change the RNAV requirements for the Navy. The option has been exercised. Thus, this section was used as a guide for the performance to Task 3 - Derive DGPS Technique and DGPS Data Link Content, Task 8 - Derivation of CDU Entry and Display Requirements, and Task 9 - Derivation of Flight Instrument Interface Requirements.

The MAGR requirements specification was also reviewed to determine the MAGR's compatibility with possible pseudolite signals as derived in Appendix III of this report. The results of that review are given in that appendix.

2.5.3.2 RCVR 3A Software Requirements Specifications The receiver pre-processor CPCI development specification was reviewed to determine the effect of pseudolite signals derived in Appendix III of this report on the MAGR and RCVR 3S receiver processing. The results to that review are given in that appendix.

An overall receiver/processor CPCI development specification was reviewed an NADC to aid in the determination of the UE's ability to handle moving waypoint updates. No useful information was found on the subject.

---

[38]Vectored Waypoint Analysis Objectives and Approach, prepared for the Naval Air Development Center Communication Navigation Technology Directorate, Code 401, by Intermetrics, Inc., Warminster, PA, 1 March 1983.

[39]E-Systems data sheet for the FRPA-3, presented by Teledyne Ryan Electronics in the Interim Design Review for the V-22 OSPREY AN/APN-217(V)5 Doppler Radar/GPS Navigation System, 18 April 1989.

2.5.3.3 RCVR 3A and MAGR Antenna Electronics Development Specifications These specifications were reviewed to determine the signal level and dynamic range capabilities of the AE-4. This information was used in Task 4, Derivation of Pseudolite Signal Structure, to determine signal level saturation levels in the AE-4 and the signal level outputs of the AE-4. The results of that review are documented as part of the documentation of Task 4.

2.5.3.4 FRPA3 Antenna Development Specification The FRPA3 antenna specification was reviewed to determine its ability to receive pseudolite signals at low and negative elevation angles. However, gains below 10° elevation angle. This specification was also reviewed to determine the FRPA3's ability to receive the higher powered pseudolite signals when close to the pseudolite. It was found that the signal levels that the FRPA3 is required to withstand are much higher than the pseudolites would be required to transmit.

2.5.3.5 1553 Bus ICD for the MAGR The 1553 bus ICD, IRN 003 draft, which is applicable to only the MAGR, was reviewed, as part of Task 3, to determine the content and associated protocol of the messages pertaining to waypoint definition and designation. The results of that review are documented in the documentation of the results of Task 3.

The 1553 bus ICD was also reviewed, for inputs to Task 8, to determine existing CDU interfaces, since the MAGR only interfaces to CDUs via the 1553 bus in the Navy configuration.[40] The results of that review will be documented as part of the documentation of the results of Task 8.

It was also indicated by NADC that, in some Navy aircraft configurations, the MAGR will not interface directly with the flight instruments. In these cases, it is assumed that the mission computer on board the aircraft will be deriving the steering information based on information supplied by the MAGR via the 1553 bus. The 1553 bus ICD was reviewed, for inputs to Task 9, to determine the existence of that information. The results of that review will be documented as part of the documentation of the results of Task 9.

2.5.3.6 ARINC 429 ICD The ARINC 429 ICD was reviewed as part of Task 9 to determine the content of the output to the flight instruments for two purposes. The first was to verify that the outputs required for the pilot to perform tasks associated with DGPS as a replacement for Shipboard TACAN and RNAV. This was verified. The second was to verify the those outputs were also available via the 1553 bus for the same reasons for those host vehicles where the MAGR did not interface with the ARINC 429.

2.5.3.7 Description of the RCVR 3M There are two papers in the open literature that provide a description of the RCVR 3M, which is the Non-Developmental Item (NDI) version of the MAGR. The first of the two papers (Gray and Forseth) provides more of a functional description of the hardware and software. Other than providing general information about the receiver, this paper provided little information pertinent to this study. The second paper (Frank and Yakos), on the other hand, provides more detail on the signal processing capabilities of the receiver. It provided useful information with regards to its automatic gain control and pulse suppression and clipping capabilities. This information was used in Task 4 to determine the effects that strong pseudolite signals have on the processing of GPS satellite signals. This paper also provided information on the MAGR's ability to track signals with a large frequency offset, a capability that would be useful in reducing potential interference from pseudolites.

2.5.3.8 Descriptions of the RCVR 3A and RCVR 3S These two papers essentially provide similar information for the older RCVR 3S and RCVR 3A that the Frank and Yakos paper does for the RCVR 3M to a lessor degree. This information was also used in Task 4.

[40]Private Communication with NADC personnel.

2.5.3.9 Features and Capabilities of the RCVR 3A and RCVR 3S This paper summarizes the area navigation (RNAV) capabilities of the RCVR 3A, along with a summary description of the inputs and outputs via the 1553 and flight instruments buses. This information was used for Task 3 to define the required data link data content, and used for Tasks 8 and 9 to determine the CDU Entry and Display requirements and Flight Instruments Interface requirements.

2.5.3.10 Description of the Area Navigation Capability of the MAGR This paper gives a description of the MAGR's RNAV equations and procedures. It was written before the MAGR award was given to Rockwell International, so it probably really describes the implementation in the RCVR 3A. However, it is a detailed discussion and it did provide information useful for the performance of Task 3 to define the requirements for data link data content, and for the performance of Tasks 8 and 9 to determine the CDU Entry and Display requirements.

2.5.3.11 Description of the RCVR 3A and RCVR 3S Receiver Processing Algorithms This paper provided much more detail on the receiver processing algorithms than is given in the RCVR 3A software requirements specifications described in Section 2.5.3.2 above. Thus, this paper was used to augment the determination of the effect of pseudolite signals derived in Appendix III of this report on the MAGR and RCVR 3S receiver processing. The results of this review are given in that appendix.

2.5.3.12 Description of the RCVR 3A and RCVR 3S Software This paper provides no additional useful information to that provided in the papers described in Sections 2.5.3.8, 2.5.3.9 and 2.5.3.10 above.

2.5.3.13 Vectored Waypoint Analysis Report This report, is basically a test plan for the IOT&E test and evaluation during the Phase II GPS UE development program. Although this is a relatively old document, it did provide some insight to how the RNAV function will be performed at sea, and how the moving waypoints could be used. The information from this report was used in the performance of Task 3 to define the requirements for data link content, and for the performance of Tasks 8 and 9 to determine the CDU Entry and Display requirements.

2.5.3.14 Data Sheet for the FRPA3 Antenna Whereas the FRPA3 antenna development specification specified the required antenna pattern, the data sheet for the FRPA3 provided actual antenna patterns based on test results. This information was used in the evaluation of required pseudolite signal transmission power levels in Task 3.

THIS PAGE INTENTIONALLY LEFT BLANK

2.6 Review of Shipboard Equipment Specifications

This task consists of reviewing exiting Shipboard Equipment (SE) specifications and interface control documents (ICDs) to determine the SE capability to operate in a DGPS environment and/or with pseudolites, and to determine what changes to the SE are required to operate in that environment and/or with pseudolites. The goal is to minimize changes.

2.6.1 Documents Reviewed The requirements documents reviewed specifically for this task or for Tasks 3 (Derive DGPS Technique and DGPS Data Link Content), 4 (Derive Pseudolite Signal Structure) and 10 (Derive Shipboard Equipment Requirements) are as follows:

1) Requirements specification for the Shipboard GPS receiver (RCVR 3S)[41],

2) RCVR 3S antenna electronics development specification[42],

3) FRPA3 antenna development specification[43],

4) RCVR 3S software requirements specifications[44],

5) Shipboard External Computer ICD[45].

The specifications reviewed are all requirements specifications that don't necessary contain the design detail required for the subject analysis. In fact, the information required for this study would probably only exist in government documents in the form of circuit diagrams and software code. It is not reasonable to obtain information from those sources. It is not even be reasonable to obtain those sources. However, there does exist a set of documents that is more descriptive of the SE implementation, although not official documentation. These are published papers written by the designers of the SE. These papers are on the following subjects:

1) Descriptions of the RCVR 3S[46],

---

[41]Prime Item Development Specification for the R-2331/URN Radio Receiver fo the User System Segment Navstar Global Positioning System, Specification Number CI-RCVR-3011A, Code Ident 13499, 21 March 1988.

[42]Prime Item Development Specification for the AM-7134/URN Antenna Electronics Amplifier of the User Segment NAVSTAR Global Positioning System, CI-AE-3061A, 21 March 1988.

[43]Critical Item Development Specification for the AS-3822/URN Fixed Reception Pattern Antenna 3 FRPA3 of the User Segment NAVSTAR Global Positioning System, CI-FRPA-3070A, 11 November 1987.

[44]Computer Program Development Specification for the Receiver Pre-Processor CPCI of the User Segment User Equipment NAVSTAR Global Positioning System, Specification Number CP-RPP-2516. Code Identification 13499, 31 July 1981.

[45]ICD-GPS-176, Revision A, Shipboard External Computer (MIL-STD-1397A) Interface, 30 April 1986.

[46]John W. Murphy and Michael D. Yakos, "Collins Avionics NAVSTAR GPS Advanced Digital Receiver", Proceedings of the Institute of Navigation National Aerospace Meeting, Arlington, VA, March 22-25, 1983.

J. F. Vacherlon, et al, "GPS Phase III Multi-Channel User Equipment", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

2) Features and capabilities of the RCVR 3S[47],

3) A description of the RCVR 3S receiver processing algorithms[48],

4) A description of the RCVR 3S software[49].

2.6.2 Documents Not Reviewed In the proposal for this study and the task description in the contract for this task, two other documents were listed for review. They are:

1) Software requirements document for the RCVR 3S[50],

2) The NTDS interface standard[51]

There is no necessity to review the software requirements because sufficient information existed in the other documents. The NTDS interface standard was not reviewed because the RCVR 3S doesn't really interface with NTDS. ICD-GPS-176 describes the interfaces with the Shipboard External Computer and simply uses the NTDS standard for the protocol.

2.6.3 Results of SE Requirements Review The documents listed above were reviewed to obtain specific information about the SE needed to perform this study to determine how the SE would operate with DGPS as a replacement for Shipboard TACAN. They were also reviewed to determine what changes might be required to the SE to operate with DGPS as a replacement for Shipboard TACAN. The following is a summary of the information obtained from those documents for those purposes.

2.6.3.1 RCVR 3S Requirements Specification The RCVR 3S requirements specification was reviewed to determine the receivers susceptibility to the pseudolite signals as derived in Appendix III of this report. The results of that review are given in that section.

The requirements specification was also review to determine its RNAV capability for possible implementation of ship-to-ship RNAV using DGPS. However, the only way to input moving waypoints into the RCVR 3S is manually via the CDU. Thus, adding this capability is not probable.

---

[47]G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

[48]Jeffrey C. Rambo, "Receiver Processing Software Design of the Rockwell International DoD Standard GPS Receiver", Proceedings of ION GPS-89, The Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, CO, September 27-29, 1989.

[49]R. G. Bartholomew, et al, "Software Architecture of the Family of DoD Standard GPS Receivers", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

[50]Computer Program Development Specification for the R-2331/URN Radio Receiver of the User System Segment NAVSTAR Global Positioning System, Specification Number CP-RCVR-3011A, 4 December 1987.

[51]Input/Output Interfaces, Standard Digital Navy Systems, MIL-STD-1397A, 7 January 1983.

2.6.3.2 RCVR 3S Receiver Processing Software Requirements Specification The receiver pre-processor CPCI development specification was reviewed to determine the effect of pseudolite signals derived in Appendix III of this report on the RCVR 3S receiver processing. The results to that review are given in that appendix.

2.6.3.3 RCVR 3S Antenna Electronics Development Specification These specifications were reviewed to determine the signal level and dynamic range capabilities of the AE-4. This information was used in Task 4, Derivation of Pseudolite Signal Structure, to determine signal level saturation levels in the AE-4 and the signal level outputs of the AE-4. The results of that review are documented as part of the documentation of Task 4.

2.6.3.4 FRPA3 Antenna Development Specification The FRPA3 antenna specification was reviewed to determine the FRPA3's ability to withstand the higher powered pseudolite signals when close to the pseudolite. It was found that the signal levels that the FRPA3 is required to withstand are much higher than the pseudolites would be required to transmit.

2.6.3.5 Shipboard External Computer Interface Control Document ICD-GPS-176 was reviewed to determine the data output of the RCVR 3S to the EC to evaluate its usefulness to the computation of moving waypoints for a data link broadcast to the aircraft. This information was used in Task 3 to verify the DGPS concept and the data content of the DGPS messages.

2.6.3.6 Descriptions of the RCVR 3S These two papers essentially provide general information on the RCVR 3S. This information was used in Task 4 to help determine the effect of pseudolite signals on the operation of the RCVR 3S.

2.6.3.7 Features and Capabilities of the RCVR 3S This paper summarizes the area navigation (RNAV) capabilities of the RCVR 3S, along with a summary description of the inputs and outputs to and from the EC. This information was used for Task 3 to determine if the required data link data content could be derived from the outputs to the EC. Information available via the RCVR 3S instrumentation port is also listed in this paper.

2.6.3.8 Description of the RCVR 3S Receiver Processing Algorithms This paper provided much more detail on the receiver processing algorithms than is given in the RCVR 3S software requirements specifications described in Section 2.6.3.2 above. Thus, this paper was used to augment the determination of the effect of pseudolite signals derived in Appendix III of this report on the RCVR 3S receiver processing. The results of this review are given in that appendix.

2.6.3.9 Description of the RCVR 3S Software This paper provides no additional useful information to that provided in the papers described in Sections 2.6.3.7 and 2.6.3.8 above.

THIS PAGE INTENTIONALLY LEFT BLANK

2.7 Derivation of Flight Safety Concepts

The concept of flight safety in the implementation of DGPS covers two potential problems that could cause a hazardous situation. The first potential problem is the transmission of signals that could interfere with other essential aircraft or shipboard systems. This problem is related to the TOR requirement stating, "Operation shall not degrade the performance of other platforms or force systems."

The second potential problem is one where the DGPS information might cause aircraft to converge on each other. For example, two different aircraft may be directed to the same moving waypoint. Another example is when an aircraft receives erroneous information, or none at all, each of which could cause a collision course with another aircraft or a ship. This potential problem must be solved by what is known as system integrity.

These two potential problems will be addressed here, and a concept for avoiding these problems will be derived.

2.7.1 Degradation of the Performance of Other Platforms or Force Systems Other than the potential interference that pseudolites might have on the reception of GPS satellite signals, this should not be a problem. That is because, by requirement, the data link shall be an LPI system. It is assumed that whatever data link is used, its frequency allocation is based on the fact that it doesn't interfere with any other system. Because it is required to be an LPI system, it cannot transmit any significant power at any frequency, since LPI essentially guarantees that it incorporates a spread spectrum signal. With this reasoning, only pseudolites present a potential problem.

However, in Appendix III of this report, it is shown that the signal structure of a pseudolite can be defined so that it doesn't provide adverse interference to even the GPS signal that resides in the same frequency allocation. Thus, no matter what data link is chosen, degradation of the performance of other platforms or force systems should not occur. This is essentially guaranteed by normal frequency allocation procedures.

2.7.2 System Integrity Issues The commercial aviation field deals with the problem of signal or data integrity all the time. They have addressed this problem as it relates to GPS and are continuing to address it. There has been a significant amount of work done in this area and information published about it. The first major paper on the subject appeared five years ago.[52] Basically, integrity, as described, is a real-time verification of the "signal-in-space". In other words, there is a "feedback" function that verifies that the signal and data being received by the aircraft is valid -- that is, it has integrity. However, through the certification process, they leave it up to the manufacturer of the equipment to prove that, if they receive the correct signal and the correct data, the equipment processes it properly to avoid erroneous navigation. That is, they don't want aircraft running into each other because one or both of them processed erroneous signals and data or processed them improperly.

This "feedback" function is usually realized by a ground station monitoring the transmitted navigation aid signal to verify its correctness. In the case of VOR/DME, they simply turn off the signal if it is faulty. In the case of GPS, however, turning the signal off instantaneously is impossible. Thus, instead, the goal is to transmit a signal, via a data link, that provides the user with instantaneous health of each satellite. It is up to the user to use this information properly. Of course, in general, and especially in terminal area operations, voice contact with air traffic control facilities and radar surveillance provide other feedback paths. This is also true in the case of Naval ships. However, for LPI reasons, it may be desirable to have shut down the radar facilities and minimize voice contact. This might be accomplished with an appropriate "feedback" function.

---

[52]Ronald Braff and Curtis Shively, "GPS Integrity Channel", Global Positioning System, Volume III, The Institute of Navigation, Washington, DC, 1986.

The concept on how this might be performed in the Shipboard TACAN replacement using DGPS application is illustrated in Figure 7. This figure shows two "feedback" paths – one from a data link receiver on the ship itself, and one from the data link receiver on the aircraft. One or both of these feedback paths may be necessary, depending upon the level of integrity desired.

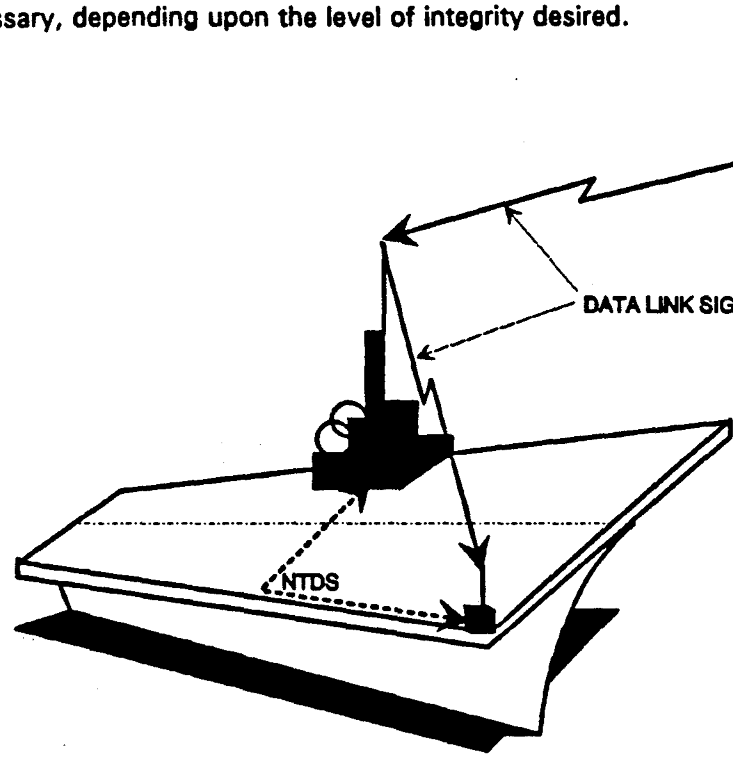

Figure 7. Shipboard Integrity Monitoring

2.7.2.1 Data Link Signal Monitoring If the only goal is to provide a passive Shipboard TACAN replacement, it would suffice to simply broadcast moving waypoints describing the ship's motion, and use some other means to designate waypoints and flight plans to be used. If that is the case, signal integrity is simply insuring that the information transmitted to the aircraft is correct. This can be accomplished by monitoring the data link signal and its messages in real time from a data link receiver on the deck of the ship via an NTDS link, which is illustrated in Figure 7. Again, this only verifies that the data link signal and its data is correct. It does not insure that DGPS is implemented accurately. For example, the aircraft's MAGR receiver may be using a different set of GPS satellites in its solution that the RCVR 3S is on the ship. The MAGR could even unknowingly be using a degraded satellite. However, with one of the enhancements presented in Section 2.3.2.2.1, the transmission of a message providing GPS PRN numbers used in the RCVR 3S navigation solution, this accurate implementation can be accomplished. This is true even if both the RCVR 3S and the MAGR are using a degraded satellite, because, in a relative sense, the navigation error would cancel. The transmission of GPS satellite PRN numbers requires changes in software in both the RCVR 3S and the MAGR, as well as the Shipboard EC to pass the information on to the data link. The RCVR 3S normally provides this information to its instrumentation port (SV tracking status), but not to its NTDS output.[53]

[53]G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

Data link signal monitoring can also be accomplished if the data link is a pseudolite In this case, the data link receiver is simply a MAGR that has been modified to receive pseudolite signals. However, the MAGR does not have an NTDS interface. Thus, the link with the shipboard computer system would have to be either a 1553 bus or via the MAGR RS422 instrumentation port. A link conversion may be required.

2.7.2.2 Data Link Feedback From the Aircraft If the DGPS concept is expanded to include the RNAV functions specified in the MAGR specification, feedback from the aircraft is essential. This feedback can be in the form of messages feeding back the information received for verification purposes, plus adding messages that provide the position and velocity of the aircraft itself. This information can be used by the air traffic controller without the use of radar during quiet periods to determine the tracks of the aircraft in the area. This information can also be used by other aircraft to perform the relative range and bearing function specified in the TOR for evaluation.

This feedback function requires no changes to the MAGR software, since all the information is available to the 1553 bus.

THIS PAGE INTENTIONALLY LEFT BLANK

2.8 Derivation of CDU Entry and Display Requirements

The MAGR does not interface with a CDU directly.[54] Figure 1 of the MAGR specification, which is the MAGR Functional Integration block diagram, indicates no interface with a CDU. All CDU entries are via a Mission or Flight Control Computer or from a "smart" CDU. Thus, CDU inputs to the MAGR are always via the 1553 bus.[55] The same is true for all CDU display outputs. As discussed in Section 2.3, with minor exceptions address in that section, all control requirements for RNAV and Shipboard TACAN replacement using DGPS are met via the 1553 bus interface input messages described in Section 2.3. Outputs that can be used to derive the required displays in a mission or flight control computer are also available via the 1553 bus interface output messages described in Section 2.3.

---

[54] Specification for NAVSTAR Global Positioning System (GPS) Miniature Airborne GPS Receiver (MAGR), Final Draft, Specification Number CI-MAGR-300, Code Identification 07868, 30 March 1990.

[55] Private communication with NADC personnel.

THIS PAGE INTENTIONALLY LEFT BLANK

2.9 Derivation of Flight Instrument Interface Requirements

On Navy aircraft, the MAGR may or may not interface directly with the aircraft's flight instruments. In some cases, this interface may be via the 1553 bus via a Mission or Flight Control Computer. On some aircraft, however, the MAGR interfaces with the flight instruments via an ARINC 429 interface specified in ICD-GPS-073.[56] This document specifies ARINC 429 Mark 33 DITS data outputs. This interface is a one way interface, only.

2.9.1 ARINC 429 Data Outputs The MAGR provides for the output of serial digital data words to the ARINC 429 data port. This output is primarily intended to drive the host vehicle's digital electronic flight instruments. However, for aircraft with analog flight instruments, this port will drive an appropriately designed digital-to-analog (D/A) converter. The data output comes in to forms -- discrete data and data words.

2.9.1.1 Discrete Data The discrete data word provides the following information:

1) Flight Mode Indicators to establish the sensitivity of the steering displays,

2) Validity,

3) Waypoint and course status, specifying whether or not they have been selected for the destination,

4) Self Test Sequence,

5) 2D/3D Navigation Indicator,

6) Navigation leg switching alert indicating the approach to a waypoint,

7) Vertical Maneuver Alert,

8) Figure of Merit indicating the quality of the navigation solution,

9) Sign/Status Matrix indicating To, From, Below, Above, etc, plus other status and warnings.

2.9.1.2 Output Data Words The output data words provide the following information:

1) GPS Height Above Reference Ellipsoid,

2) Distance To Go,

3) Waypoint Bearing (True).

4) Vertical Deviation,

5) Desired Track,

6) Cross Track Distance,

---

[56] GPS User Equipment -- Digital Flight Instruments (ARINC 429) Interface, Revision A, NAVSTAR GPS Phase III Interface Control Document ICD-GPS-073, 31 March 1986.

7) Magnetic Heading,

8) True Heading,

9) Time To Go,

10) Present Position Latitude,

11) Present Position Longitude,

12) Track Angle (True),

13) Ground Speed,

14) Horizontal/Vertical Deviation.

2.9.2 Matching ARINC 429 Interfaces to MAGR RNAV and Shipboard TACAN Replacement Requirements
The ARINC 429 outputs listed above meet the flight instrument interface part of MAGR RNAV requirements specified in the MAGR Specification, which also meet all Shipboard TACAN replacement requirements.

2.9.3 Flight Instrument Interface Requirements via the 1553 Bus All of the outputs specified above for the ARINC 429 interface are also available via the 1553 bus in one message or another. Thus, the flight instrument interface requirements for RNAV and Shipboard TACAN replacement are also met using the 1553 bus. However, in this case, a combination of 1553 bus output messages described in Section 2.3 make up the information that would have been provided by the ARINC 429 interface, while the mission or flight control computer either provide the ARINC 429 interface or control the flight instruments directly. GPS height above the reference ellipsoid, present position latitude and longitude, ground speed and figure of merit are available via a variety of the following 1553 bus interface output messages:

1) G-6 GPS Foreground Navigation Output Message,

2) G-8 Background Navigation Data Output Message 1 (ECEF),

3) G-9 Background Navigation Data Output Message (Lat/Long),

4) G-15 Time Mark Pulse Output Message 1,

5) G-17 Data Capture Pulse Output Message 1.

2.10 Derivation of Shipboard Equipment Requirements

The reviews and derivations of Tasks 1 through 7 yield three options for Shipboard Equipment Requirements. No specific data link has been chosen, except for the possibility of using pseudolites, which is one of the options. The options are associated with the extent to which the Shipboard TACAN replacement using DGPS is applied to the RNAV function. If TACAN is simply replaced with DGPS, then only a one way broadcasting type data link, such as a pseudolite, is required. If the application of DGPS goes beyond that and is made part of the overall RNAV function, then a two way data link with responses from the airborne equipment is required. Since the RNAV function using the MAGR receiver is currently being upgraded, this latter option makes sense, especially since DGPS can enhance the RNAV function quite accurate. With the right implementation, it is conceivable that non-precision, or even precision approaches are possible.

2.10.1 DGPS Options The three DGPS options are as follows:

1) The use of a conventional data link for broadcast transmission of DGPS information. The broadcast DGPS information is limited to the following:

a) Moving waypoint definitions describing the ship's trajectory,

b) Optional addition of GPS satellite PRN numbers used in the RCVR 3S GPS navigation solution and the uncertainties in that navigation solution.

2) The use of a conventional data link for two-way communication with the aircraft for transmission of RNAV information derived from DGPS information. The data transmitted to the aircraft is whatever is required for the RNAV function, consisting of the following, as a minimum:

a) Moving waypoint definitions describing all waypoints in a flight plan,

b) Destination designation messages describing how and what waypoints to use,

c) Flight plans,

d) Optional addition of GPS satellite PRN numbers used in the RCVR 3S GPS navigation solution and the uncertainties in that navigation solution.

The data transmitted from the aircraft to the ship is also whatever is required for the RNAV function, consisting of the following, as a minimum:

a) Waypoint data verifying the receipt of waypoint definitions,

b) Destination data verifying the receipt of destination designation messages and bearing and range to the destination,

c) Flight plan/profile data verifying the receipt of flight plans,

d) Optional addition of MAGR GPS navigation solution (position and velocity) and Figure of Merit (FOM) representing the uncertainty in that navigation solution,

e) Optional addition of GPS satellite PRN numbers used in the MAGR GPS navigation solution.

The data in e) would alert the RNAV function on the ship if the MAGR is not using the same GPS satellites in its solution as is being used for the waypoint definition.

3) The use of a pseudolite for broadcast transmission of DGPS information. The broadcast DGPS information is limited to the following:

a) Moving waypoint definitions describing the ship's trajectory,

b) Optional addition of GPS satellite PRN numbers used in the RCVR 3S GPS navigation solution and the uncertainties in that navigation solution.

Two way communication is not possible using pseudolites. Thus, the RNAV option is not available using pseudolites.

2.10.2 Shipboard Equipment Requirements The Shipboard Equipment requirements for each of the three DGPS options are described as part of the overall DGPS system specification in Appendix VI.

2.11 Derivation of DGPS UE Requirements

If Pseudolites are not used as a data link for the replacement of Shipboard TACAN with DGPS, no new requirements are necessary for the MAGR. This was found to be true from the review of the MAGR specification[57] and the draft MAGR version of the 1553 Bus ICD,[58] now that the new RNAV option has been exercised. However, the replacement of Shipboard TACAN with DGPS does place requirements on other elements of the host vehicle, namely the mission computer and the data link to be used for the communication of RNAV information. Since these elements are part of the "DGPS System", their requirements are specified in Appendix VI. These requirements are summarized here.

2.11.1 Host Vehicle Mission Computer Requirements The Host Vehicle Mission Computer shall provide the interfaces:

1) Between the MAGR and the data link providing RNAV information,

2) Between the MAGR and the Control and Display Unit (CDU).

3) Between the MAGR and the Flight Instruments (on certain Host Vehicles).

The last two requirements are for functions that are independent of the replacement of Shipboard TACAN and are assumed to be already satisfied.

As mission computer interface between the MAGR and the data link includes the following functions:

1) Control the 1553 bus,

2) When data link receives a message, establish of a protocol with the data link via the 1553 bus,

3) Receive messages from the data link,

4) Checking parity of the received messages and taking appropriate action based on that check,

5) Decode the header information of the received messages to determine its content,

6) Based on the content received, construct the appropriate 1553 bus message for the MAGR,

7) Establish a protocol with the MAGR. This protocol includes the control of the MAGR's Basic Waypoint and Flight Plan data bases.

8) Communicate the reconstructed messages to the MAGR via the 1553 bus,

9) Accept response messages from MAGR via the 1553 bus,

10) Request additional messages from the MAGR via the 1553 bus,

---

[57] Specification for NAVSTAR Global Positioning System (GPS) Miniature Airborne GPS Receiver (MAGR), Final Draft, Specification Number CI-MAGR-300, Code Identification 07868, 30 March 1990.

[58] NAVSTAR GPS Phase III Interface Control Document, GPS User Equipment - MIL-STD-1553 Multiplex Bus Interface, ICD-GPS-059, Revision B, IRNs 001, 003 and 004, Draft MAGR Version, 14 June 1991. This draft MAGR version defines the CI-MAGR-300 RNAV requirements implementation as of that date.

11) Strip data out of the messages not pertinent to RNAV and air traffic control,

12) Add headers and parity and format messages for output to data link,

13) Establish protocol with the data link and command transmission of messages.

Details of these requirements are given in Appendix VI along with the other DGPS System requirements. The content of the messages are described in Section 2.3.2.1 and Appendix IV.

2.11.2 Host Vehicle Data Link Requirements Data link requirements are specified in Appendix VI along with other DGPS System requirements.

2.11.3 MAGR Requirements for Use with Pseudolites Pseudolites are not recommended as a data link for the replacement of Shipboard TACAN with DGPS. However, in event that they were to be used, the requirements specified above for the Host Vehicle Mission Computer and Data Link no longer apply, and the following requirements are placed on the MAGR.

1) The MAGR shall generate coder states for the five P-codes specified as being reserved for Ground Transmitters in ICD-GPS-200B.[59] In addition, based on Pseudolite identification (ID), these coder states shall include delays to various times of the week other than the current time of week. The MAGR shall also have the capability of positioning the P-coders to those generated coder states.

2) The MAGR shall have the capability of encrypting the generated P-codes using the Auxiliary Output Chip (AOC).[60]

3) The MAGR shall select a Pseudolite code based on a data base containing Pseudolite IDs for the various Naval ships as directed by the Operator.

4) The MAGR shall estimate the range to the Pseudolite for the purpose of estimating the received code phase for acquisition of the Pseudolite signal.

5) The MAGR shall have the capability of acquiring the received Pseudolite signal, which will be synchronized to GPS time to within 100 nanoseconds (1 sigma) as transmitted, in a Direct P(Y)-Code Acquisition Mode (State 2 operation). This is known as a "Hot Start" in the MAGR specification. The Pseudolites will only be transmitting the P-code on the L2 frequency.

6) The MAGR shall devote a channel to the Pseudolite signal for the purpose of obtaining RNAV information at a rate as high as 500 bits per second synchronized to the GPS one millisecond epochs. (This may require the incorporation of an AOC chip in the existing sixth channel of the current MAGR.)

7) The MAGR shall acquire and track the selected Pseudolite signal at a range of 300 nm from the

---

[59]ICD-GPS-200B, NAVSTAR GPS Space Segment/Navigation User Interfaces, 30 Nov 1987.

[60]ICD-GPS-224, Selective Availability and Anti-Spoofing Receiver Requirements with Appendix III, Communications Security (SECRET), 15 December 1988.

ICD-GPS-222, Interface Control Document for the NAVSTAR Global Positioning System User Equipment Auxiliary Output Chip (Secret), June 1985.

pseudolite at a received $\frac{J}{S}$ level of 41 dB. The transmitted power of the pseudolite will be commensurate with that level.

8) The MAGR shall be capable of decoding the Pseudolite signal data at rates of up to 500 bits per second. The Pseudolite signal may have error detection and correction encoding different than that specified in ICD-GPS-200B.

9) The MAGR shall utilize the Precise Positioning System-Security Module (PPS-SM) for decryption of the received Pseudolite data.

10) The MAGR shall be capable of processing the RNAV data collected from the Pseudolite signal just as though it was received via the 1553 data bus, but with a different data format.

11) The MAGR shall autonomously assign waypoint numbers to those waypoints received on the Pseudolite signals.

These requirements are repeated in Appendix VI along with the other DGPS System requirements for completeness.

THIS PAGE INTENTIONALLY LEFT BLANK

2.12 Generation of a System Specification

Outputs of Sections 2.3, 2.4, 2.7, 2.8, 2.9, 2.10 and 2.11 and appendices referred to in those sections are organized into a stand-alone GPS System Specification for Shipboard TACAN Replacement, which appears in Appendix VI. This appendix includes the statement of requirements on the MAGR, the mission computer, the data link and the shipboard equipment.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX I

EDITED EXCERPTS FROM

CONCEPTS FOR REPLACING SHIPBOARD TACAN WITH DIFFERENTIAL GPS

BY

DR. A. J. VAN DIERENDONCK

PRESENTED AT

ION GPS-90

ION SATELLITE DIVISION
3RD INTERNATIONAL TECHNICAL MEETING

COLORADO SPRINGS, COLORADO

SEPTEMBER 17-21, 1990

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

1.1.0 Introduction

The capability of GPS as a replacement of ground-based TACAN has not been hard to visualize or justify, even without the use of DGPS. DGPS only improves the accuracy (and integrity) of the application. This concept and testing of the concept for civil aviation is not new.[1,2] And, of course, one of the objectives of DoD testing is to validate the concept of navigating with respect to fixed waypoints, which is basically the capability that TACAN provides. Their use of moving waypoints has also been demonstrated, primarily for rendezvous, which, in a sense, is also the capability that shipboard TACAN provides in a limited way.

Rendezvous, as described above, requires an a priori knowledge of the rendezvous location, even if it is moving. Shipboard TACAN could, but doesn't, to the author's knowledge, provide real-time knowledge of the ship's location, primarily because the TACAN transmitter is slaved to the ship's direction of travel, rather than magnetic north to which airborne TACAN units navigate. The pilot must obtain the ship's heading by other means and account for it for navigational purposes. Of course, this requires communication with the ship in some form or another.[3]

The same is true for GPS for real-time rendezvous. However, GPS has the advantage of being developed at a time when technology allows for automatic real-time communication to perform this function. In fact, this real-time communication also provides a means for significant enhancements to this rendezvous problem, providing information that would greatly reduce the pilot's workload. One of these enhancements, of course, is the increased accuracy provided by the use of DGPS. Other enhancements include providing ship velocity and heading information for the aircraft's approach to the ship.

DGPS, as described herein, is not the classical DGPS as envisioned and developed by the Radio Technical Commission for Maritime Users (RTCM).[4] The RTCM's version of DGPS is one where corrections to the GPS measurements are transmitted to the user to provide him the capability to cancel the GPS errors. These corrections are determined by a stationary reference station at a known surveyed location. In the case of the shipboard application, however, the ship serves as the reference station, but its location is not accurately known -- only to the accuracy of its own GPS solution, which is constantly changing. Even so, a different form of DGPS is possible, one that provides the ship's location to the user, providing him a reference for relative navigation. Other information can also be provided, such as satellite selection, to make this navigation even more accurate.

The concept of using DGPS as a replacement for shipboard TACAN is illustrated in Figure I.1, where both the ship's GPS receiver/navigator and the airborne GPS receiver/navigator are tracking the same GPS satellites, although this is not necessarily essential and depends upon the accuracy desired. The required information is transmitted from the ship via a real-time data link. The requirements for this data link and data transmitted via that link are the main thrust of this paper.

1.2.0 DGPS Application

1.2.1 "Differenced" DGPS As stated above, the DGPS technique applicable to this relative navigation concept is not the one developed by the RTCM, but one coined as "differenced DGPS" by Reference 5, although in that report the operation is the reverse of this application -- the airborne receiver reports its location and the ground station derives range and bearing to the aircraft for its use in air traffic control. In this application, the ship would transmit its GPS location to anyone that is "authorized" to listen. The airborne user would then difference his GPS location with the transmitted ship location to derive relative range and bearing to the ship. The accuracy to which this can be accomplished is a function of what other information is transmitted by the ship, such as velocity, heading, satellites used in its solution, etc. As a matter of fact, the ship's location transmitted wouldn't even have to be the ship's GPS location, depending upon the accuracy required. But then, since all the applicable ships will probably have GPS for navigation, there is no reason why the transmitted location shouldn't be the GPS location.

The word "authorized" in reference to the location is important, since obviously the ship's location may be extremely sensitive. This leads to a requirement to encrypt the transmitted data, if not the data link itself. There may even be a requirement for a "covert" low-probability-of-intercept (LPI) data link for the same reason, which leads to a requirement for at least using spread spectrum techniques for the transfer of data. Both of these requirements are independent of DGPS requirements and are reserved for later discussions.

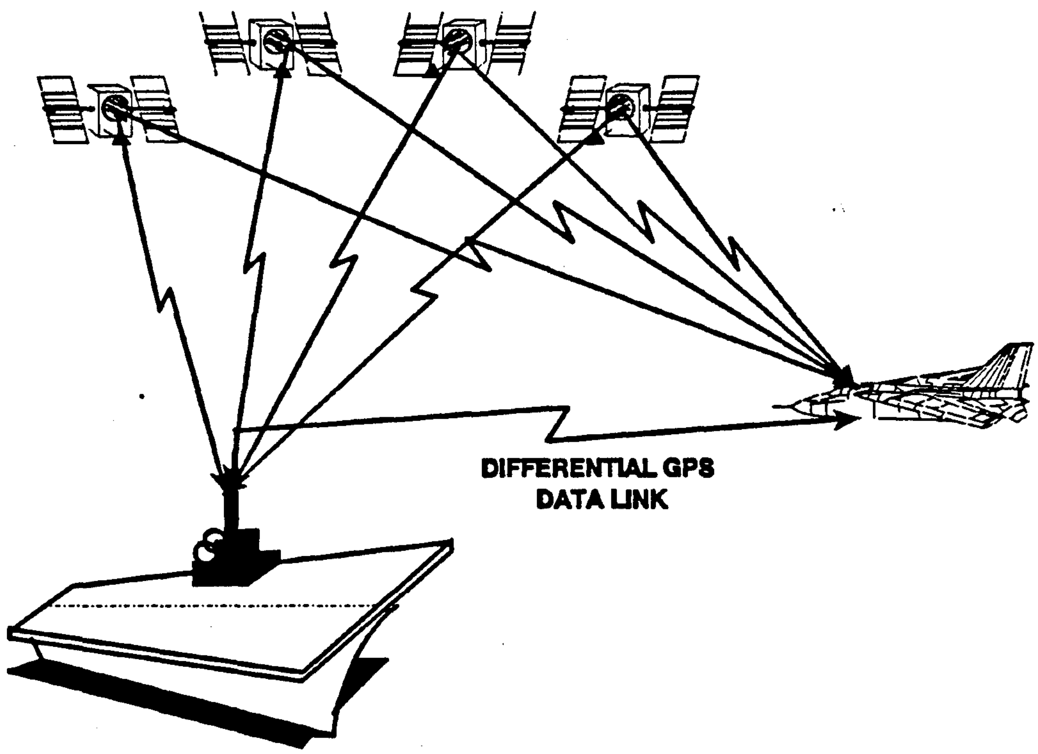

Figure I.1. Shipboard DGPS Concept

Given the limitation of tracking only four satellites in the airborne GPS receiver, this differenced DGPS mode of operation can be just as accurate as the DGPS method developed by the RTCM, provided that the data transmitted from the ship contains the right information. This information is as follows:

1) In addition to current time-tagged location, velocity and other derivatives are also transmitted to project the ship's location to the time that the airborne receiver determines relative range and bearing.

2) The GPS satellite identifications (IDs) used in the ship's solution for the above parameters are also transmitted, so that the airborne receiver, if it wishes, can perform its solution using the same satellites. This eliminates the differential errors between satellites.

The requirement for velocity and higher order derivatives is a trade-off between accuracy and the data link's data bandwidth. For example, if the ship's dynamics are low enough, coupled with no need for ultimate accuracy, there is no need for this information and the data link's data bandwidth can be relatively narrow. However, at the same time, if the data link's data bandwidth is high, there also is no need for this information because the ship's location data would never be dated. The need arises when the data bandwidth is relatively narrow and there is a need for ultimate accuracy.

The need for satellite IDs would only be required to achieve the ultimate accuracy of DGPS, in the case when all GPS bias type errors need to be removed. Without the IDs, the differenced DGPS accuracy would still be better than the published stand-alone GPS accuracy, because it is likely that there would be some overlap between the ship's GPS receiver's satellite selection and that of the airborne receiver's selection. The key factor here is whether or not either receiver would be using a "degraded" satellite. If both receivers were using the same set of satellites, the DGPS error is minimized, even if a "degraded" satellite is used. Thus, this feature of providing satellite IDs provides a built-in integrity to the RNAV solution.

Finally, there is the question of what ship location should be transmitted. The ship's GPS solution is probably other than that of the ship's aircraft landing spot. Thus, in order to provide that location, and its derivatives, to the airborne receiver, ship attitudes and attitude rates are required for transformations to that location. These computations should be performed on the ship before transmission of the DGPS data for the purpose of off-loading the data link and the airborne receiver's computations.

1.2.2 Enhanced DGPS The "differenced" DGPS described above would only provide the airborne user with range and bearing to the ship or the location of the ship's aircraft landing spot, possibly enhanced with velocity information to provide a rate-of-change of that location. Depending upon the data transmission capabilities of the data link, other information could also be transmitted that could enhance the RNAV capability of this DGPS application. There are probably many enhancements that could be dreamed up using the ability of transmitting additional data. One that definitely comes to mind is the vectoring of the aircraft on its final approach to the ship's runway or landing pad. This is already a capability, although an awkward one, using TACAN with the addition of voice transmissions to the aircraft's pilot. Since GPS, and DGPS, has a three dimensional capability, this would also include glide slope information, which doesn't exist with TACAN.

The concept is shown in Figure I.2, utilizing additional moving waypoints (two shown, but more could be provided -- DoD's airborne receiver, RCVR 3A, has a capability for nine[6]). These moving waypoints that follow the ship and its heading can be used to align the aircraft to its direction for landing. The second waypoint essentially provides a moving "outer marker". All of this could be provided without any voice transmissions.

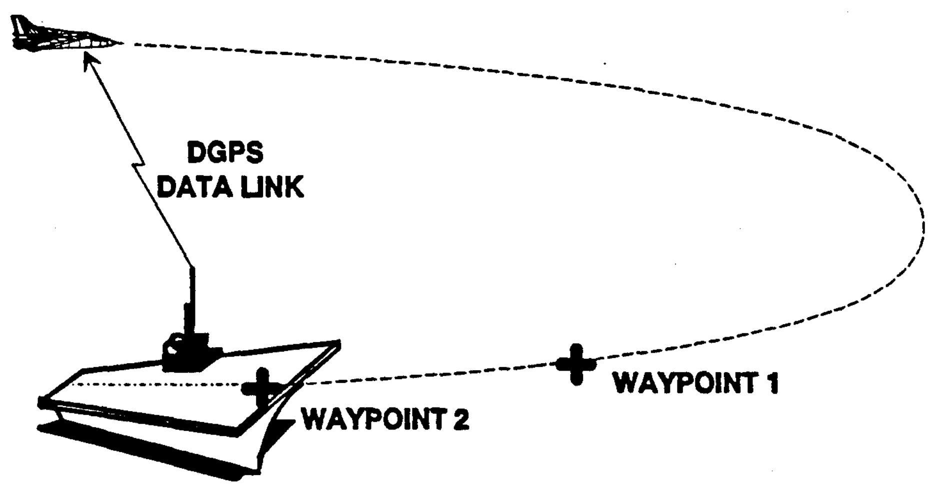

Figure I.2. The Use of DGPS for Approach Alignment

I.3.0 DGPS Data Link Requirements

There are a number of factors to consider for DGPS data link requirements. These are:

1) Data transmission rates (bandwidth)

2) Data and/or link encryption

3) Reception reliability

4) Aircraft integration

5) Shipboard integration

6) Impact on airborne GPS receiver design and implementation

7) Low probability of intercept.

I.3.1 Data Transmission Rates The first factor, data transmission rates, was discussed earlier as being a trade-off against DGPS accuracy. However, it is expected that any modern data link employed will provide enough bandwidth. The exception to this that will be considered in this paper is the use of pseudolites for the data transmission at one of the GPS frequencies, primarily because of airborne GPS receiver design constraints. This is because that receiver would also be used for the reception of the DGPS data.

I.3.2 Encryption The second factor, encryption, is a necessity so that any unauthorized individual cannot obtain the information in the DGPS data link message, primarily the location of the ship. This can be accomplished in one or both of two ways:

1) Data encryption

2) Spread spectrum code encryption

3) Or both

It would be highly desirable if the encryption techniques used would be identical to those used on the GPS signals from the satellites, so that the same keys can be used, thus minimizing the impact on implementation of encryption. Of course, this capability would have to be endorsed by the National Security Agency (NSA). In fact, if pseudolites were used as the data link, this would be a natural procedure, especially if the pseudolites would transmit the data on a GPS P-Code. The airborne receivers already have the capability to track encrypted P-Codes, as well as the capability to decrypt navigation data. If another data link were used, the data transferred from that link to the GPS receiver could also be decrypted using the same algorithms by the airborne receiver. However, the data link receiver itself would have to handle any encrypted code modulation.

I.3.3 Reception Reliability Here, reception reliability does not mean the reception of the GPS satellite signals, but the reception of the DGPS data link signal by the airborne data link receiver, as well as its electromagnetic interference (EMI) effect on other systems, which includes GPS. The reliability of the reception of the DGPS data link signal by the airborne user directly affects the integrity of using GPS as a replacement for shipboard TACAN. However, in a sense, the intermittent loss of DGPS messages is not catastrophic, since previously received messages can be used to project the ship's location during the loss. Thus, whatever data link is used, the degradation due to signal loss is a graceful one. Furthermore, because signal reception power varies inversely with the square of the distance from the transmitter, it is more likely that any intermittent loss would occur at larger distances. Fading due to multipath would be one exception to that rule.

Special consideration to the possibility of signal loss must be given to the use of pseudolites for the DGPS data link. This is because of the location of the GPS antenna on the aircraft for GPS satellite signal reception. The gain of that antenna towards the direction of the ship will be much less than the gain towards the satellites. In fact, if the aircraft is at higher altitudes, the gain could vary through backlobes of the antenna pattern, although that shouldn't occur as the aircraft approaches the ship. One solution to this is to increase the power output of the pseudolite, while another solution is to install a second GPS antenna on the underside of the aircraft. The first solution may be acceptable, but certainly would increase the probability of signal intercept. The second solution could be unacceptable from the view of aircraft integration, but maybe more acceptable than the installation of a new data link.

As far as EMI effects are concerned, it is assumed that this problem has already been solved with respect to the use of existing data links, and would be in the case of any newly designed data link. The exception to that may be the use of pseudolites. Since pseudolites would transmit at one or both of the GPS frequencies, they certainly could interfere with the airborne GPS receiver, as well as the shipboard GPS receiver. However, this interference can be minimized to a tolerable level, as will be shown later.

I.3.4 Aircraft Integration Aircraft integration was eluded to above, and is a difficult subject to address without knowing what data links exist that might be used for transferring DGPS data. It is true, however, that the use of a pseudolite for this purpose could very well minimize the aircraft integration requirements, provided that an additional antenna is not required. In this paper, no attempt is going to be made to solve the aircraft integration problem.

1.3.5 Shipboard Integration This is also a difficult subject to address without knowing what data links exist that might be used for the transfer of DGPS data. However, this problem is not as severe as the aircraft problem because of the smaller number of installations. Also, if shipboard TACAN is to be replaced, obviously some sort of integration will be required, if for no other reason than to transfer GPS information from the shipboard GPS receiver to an existing data link. No attempt will be made to solve the shipboard integration problem in this paper, although some discussions related to the problem are given below with respect to the use of a pseudolite as the data link.

1.3.6 Impact on Airborne GPS Receiver Design and Implementation The desire has been stated by the U. S. Navy to minimize the impact on airborne GPS receiver design and implementation for the replacement of shipboard TACAN. However, at least some software modifications may be required to do so, no matter how the replacement is realized, especially if it is to work well. A goal would to make it work much better than TACAN works, given the additional capabilities that exist using DGPS. It is conceivable that no changes are required of the GPS receiver if the aircraft's mission computer performs the functions. At this time, that is also an unknown. Furthermore, its software would have to be modified.

The use of pseudolites for the data link would definitely have a larger impact on the airborne GPS receiver design and implementation than the use of another data link. This is because the GPS receiver would have to receive the signals, decrypt the messages, decode the messages, and then act on them. Since these receivers can already accommodate moving waypoints, the relative navigation capability already exists, once the waypoints are determined.

1.3.7 Low Probability of Intercept (LPI) Transmitting from a ship in any form presents problems in that those transmissions can be detected by an other than friendly forces. Strong signal transmissions present even larger problems. If one were to only provide a replacement for shipboard TACAN that is no more detectable than TACAN transmissions, it would be a non-problem. TACAN can be detected from space. Thus, the requirement for LPI of transmitted signals is a desire, all be it a very strong desire. The high probability of intercept of the TACAN signals does present problems, so much so that it has to be turned off if the ship's location is sensitive. Thus, this is one area where replacing TACAN with DGPS could provide a significant benefit, even though DGPS does require transmission of information. This is because the current state of technology provides spread spectrum capabilities not available at the time TACAN was developed. Other "covert" communication technologies are probably available as well, but that point will not be dwelled upon here.

The advantage of spread spectrum communications is well known. The simple fact that the transmission energy can be spread over a wide frequency range provides the capability to receive signals well below ambient noise, thus making the signal more difficult to detect by unfriendly forces, unless, of course, they would know how to "despread" the signal. This can easily be avoided by encrypting the spreading codes. Many of the existing modern communication systems have such a capability and certainly could be used for the DGPS data link if appropriate for that purpose. Although it is true that the transmitted spread signals can certainly be detected close to the transmitter, or via the use of narrow beam directional antennas, they would be quite effective to significant degree as LPI transmissions.

Since the GPS signal structure makes use of spread spectrum Code Division Multiple Access (CDMA) techniques, the use of pseudolites transmitting GPS like signals will provide a data link with a degree of LPI capability. Even if the pseudolite transmission is made up of higher energy pulses, which will be shown later as being a necessity, if the timing of the pulses are not known to the interceptor, he can only detect the average power of the pseudolite signal in its bandwidth. The degree to which a pseudolite data link can provide an LPI signal will be derived in later discussions.

1.3.8 References

1. C. Shively, "Real Time Simulation of a Low Cost GPS Navigator for Nonprecision Approaches", Global Position System, Volume I, The Institute of Navigation, 1980.

2. Steven D. Campbell and Raymond LaFrey, "Flight Test Results for an Experimental GPS C/A-code Receiver in a General Aviation Aircraft", Global Position System, Volume II, The Institute of Navigation, 1984.

3. Jeff Wallin, U. S. Marine Reserve Helicopter Pilot, Private Communication.

4. Rudolph M. Kalafus, A. J. Van Dierendonck and Nevin A. Pealer, "Special Committee 104 Recommendations for Differential GPS Service", Global Position System, Volume III, The Institute of Navigation, 1986.

5. Bryant D. Elrod, Stephen B. Heppe and Robert J. Kleinhenz, "Application of Differential GPS to the Marine Air Traffic Control and Landing System, Phase II Study", Final Report, Stanford Telecom TR890102, 30 November 1988.

6. G. Krishnamurti and D. E. Gray, "Features and Capabilities of the DoD Standard GPS Receivers for Aircraft and Seaborne Applications", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987."

APPENDIX II

LOW PROBABILITY OF INTERCEPT (LPI) REQUIREMENTS

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

II.0 A Philosophy of Low Probability of Intercept

LPI is an elusive requirement because LPI is hard to define. It depends greatly on how one defines the equipment or system that is used to perform the intercept. Furthermore, there is a difference between detection, intercept and exploitation, as described in Reference 1.[1] Probability of Detection is the probability of detecting the existence of signal transmission. Probability of Intercept is the successful identification of the transmission. Then, Probability of Exploitation is the ability to extract intelligence from the transmission. There is a fine line between the Probability of Detection and the Probability of Intercept, and sometimes they are used interchangeably. At best, the Probability of Intercept is the detection of certain characteristics of the signal that allows the observer to identify the transmission. However, to do a good job of detection, some knowledge of the signal structure is required, and thus, the transmission is automatically identified. Thus, in this study, we will consider the probability of detection and intercept to be one and the same. Exploitation will not be considered, except that only signal structures that minimize the Probability of Exploitation will be considered. Some comments on exploitation follow.

II.1 Background

II.1.1 Exploitation Exploitation is the ability to perform one of the following functions:

1) pin-point the location of the transmission,

2) "intercept" the information that is transmitted.

The first function is sometimes called triangulation -- either the measurement of the time-of-arrival (TOA) of a signal at different locations, or the measurement of the TOA and associated angle of arrival. The second function "listens" to the information being transmitted. For the subject matter of this report, that information would be the sensitive position and velocity of the ship/or aircraft. This latter function is easy to prevent with signal and data encryption, even if the observer does detect transmission. Signal and/or data encryption is an important requirement for the transmission of DGPS information.

The first function of pin-pointing the location of the transmission, on the other hand, could be more difficult to prevent because absolute denial of signal detection is very difficult. However, an observer may very well detect a transmitted signal and not be able to triangulate on that signal, at least not easily. For example, JTIDS, which is described elsewhere in this report, can easily be detected at distances greater than or equal to that of its advertised range of operation. Because of the transmitted power, and because of the exact periodicity of the pulses, TOA of the JTIDS signal can be measured quite accurately. However, because of a technique called "jitter," which randomizes the start time of its transmission, conversion of TOA to range cannot be established accurate enough to provide good triangulation, unless three observers with "good" synchronized clocks that detect the transmission simultaneously. The three TOAs can be combined to solve for the transmitter's two-dimension location and time of transmission, similar to the method used to perform a GPS solution. However, this technique does require very close coordination between observers, also requiring that all three observers detected the TOA at the same time. It also can be defeated by directing the transmission in specific directions using transmitting antenna beam forming. Furthermore, even if the signals can be detected doesn't mean that TOA measurements are that accurate. Signal detection may require a long averaging period. Then, accurate detection of the time the signal is received is not easy, especially if messages are transmitted sparingly. Of course, in periods of time when LPI is necessary, the message traffic should be kept at a minimum.

Another technique for learning the location of a transmitter is to use a narrow-beam scanning antenna to provide a bearing to the transmitter. Of course, a single bearing can be used to home-in on the transmitter, while two bearings from two locations can be used to pin-point the transmitter. The scan rate of the antenna must be slow enough to illuminate the transmitter for the interval required to detect the signal. Of course, if the signal is transmitted sparingly, this approach is not very effective, unless multiple beams are used. However, note that TOA

[1]Ralph Schoolcraft, "Low Probability of Detection Communications, LPD Waveform Design and Detection Techniques," IEEE/DoD MILCOM Proceedings, Reston, VA, 4 - 7 November, 1991.

measurements are not necessarily required. In the DGPS application, the transmissions would be infrequent, thus making this approach ineffective.

Another technique to minimize exploitation is to "spoof" the observer by establishing low value platforms that send spurious JTIDS pulses in addition to noise. If the levels are maintained at values that are benign to JTIDS, they can still cause interference to the observer's receivers. This technique is not used because it would also interfere with TACAN. However, TACAN is being replaced.

Because exploitation can be defeated with various techniques, exploitation here is not an issue. The concentration here will be on Low Probability of Intercept, because, if interception is denied, exploitation is automatically denied.

II.1.2 Interception Detection of the transmitted signal is almost impossible to prevent in an absolute sense, unless very wide bandwidth spread spectrum signals are used for the data link. This would require transmission at very high frequencies because the lower frequency bands have mostly been allocated. Furthermore, the very wide bandwidths would require transmission at higher frequency so that the bandwidth would be small about the transmitted frequency. High frequency transmission also has the advantage of the signals being absorbed by moisture in the atmosphere, thus preventing detection at large distances from the transmitter. Of course, that absorption also prevents using the signals at larger distances from the transmitter. Unfortunately, high frequency data links, such as ones transmitting at EHF frequencies, require high cost technologies that would prevent the production of low cost data link terminals. There are applications for such links. MILSTAR is an example. However, MILSTAR terminals do not adhere to the cost goals stated for the replacement of Shipboard TACAN with DGPS.

Another concept of LPI is to transmit in a frequency band that has a lot of transmission traffic. The result is an increase in that ambient noise background. In this case, the concept is to "hide" the transmitted signal amongst all the other transmissions so that it cannot be isolated. However, if all the other transmitters reduce transmission, this concept doesn't necessarily work.

In this study, the techniques used to detect signals will be limited to what is called radiometric interception, with some knowledge of the periodic characteristics of the transmitted signal. Furthermore, identification techniques will not be considered, primarily because the scope of the effort has to have a bound. Besides, if detection is denied, interception is automatically denied. It is also shown in Reference 1 that reducing the probability of detection will also usually reduce the probability of interception. Thus, this is a reasonable bound.

The following discussions provide the theory of how encrypted signals might be detected for the purpose of deriving LPI requirements. These discussions are followed by the derivation of a measure for evaluating the LPI capability of a data link and a summary of the LPI requirements.

II.2 Probability of Detection

As stated above, detecting wideband signals is not necessarily difficult, even if encrypted spread spectrum techniques are used to generate the wide bandwidth. For example, many GPS receivers designed for surveyors track the GPS L2 signal carrier without ever generating the P code modulated on that carrier. Thus, the fact that the P code could be encrypted does not keep them from still tracking that carrier. These users square the signal at an IF frequency or at baseband to cancel the code. This squaring process generates an IF at twice the frequency or a baseband signal with twice the doppler. Squaring cancels the code modulation, which effectively is an amplitude modulation of ± 1's. This prevents them from obtaining ranging information or the modulated data, but they can detect the signal and obtain doppler information.

If an intercept observer doesn't know how the transmitted signal is spread over its bandwidth, he must monitor the entire bandwidth, or at least a large percentage of the bandwidth, to observe all or most of the transmitted signal's power. Then, he is called a radiometric interceptor. Of course, the observer also observes all of the ambient noise in the same band. Spread spectrum communication signals are usually below the ambient noise, unless the observer is close to the transmitter. One form of the detection process is illustrated in Figure II.1.

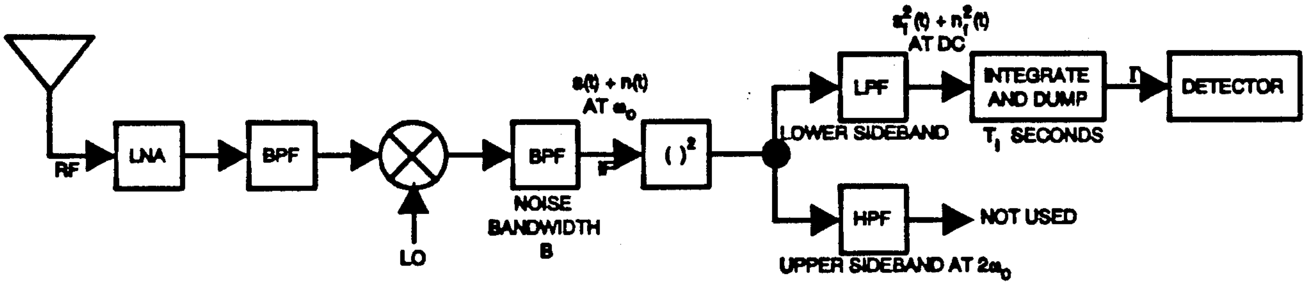

Figure II.1 Wideband Signal Detection Process

For the process illustrated in Figure II.1 is sometimes called radiometric detection, where signal detection is performed by integrating the lower sideband of the squared signal over a post-detection interval T_I, and comparing it with a threshold TH. If the resultant test statistic Γ exceeds the threshold TH, a signal is declared to be present. Otherwise, a test statistic is declared to be due to ambient noise. One could also detect the upper sideband by mixing it with the second harmonic of the known center carrier frequency. But the results are the same. Furthermore, one could also track that second harmonic to reconstruct the carrier center frequency, use it as a local oscillator (LO), mix it with the incoming signal, and then observe the modulation on the signal. However, this comes under the heading of identification. There are many problems with that. First of all, the interceptor would have to be much closer to the transmitter to derive an LO that was clean enough to observe the modulation. Second, if the information in the modulation is encrypted, this process still may not tell him anything. Also, the signal may not be transmitted all the time, and if not, his LO will disappear. Also, transmission from multiple users is the same band would create all sorts of problems for him. It for these reasons, that only the detection of energy in the lower sideband will be considered here.

As stated above, the squaring process takes place at the point where the signal-plus-noise bandwidth, known as the predetection bandwidth, is the spread spectrum two-sided noise bandwidth B of the transmitted signal. This takes advantage of all the signal's transmitted power. For a frequency hopping signal, the signal's bandwidth is only a fraction of B at any instant of time. The observer doesn't know what the instantaneous center frequency is, so he is forced to also observe ambient noise in the entire bandwidth B about both positive and negative carrier frequencies. Thus, he also observes all of the ambient noise in the same band.

The squaring process has the effect of cancelling any sign modulation of the signal. Thus, when it is integrated, it will always integrate in a positive sense. The noise also will integrate in a positive sense. However, its modulation about the center frequency of the predetection band will be much more random than that of the signal. Therefore, it will integrate up to a smaller number. The derivation of this process follows.

II.2.1 Signal and Noise Representation Let

$$s(t) = AC_I(t)\cos[(\omega_O + \Delta\omega_i)t + \phi(t)] + AC_Q(t)\sin[(\omega_O + \Delta\omega_i)t + \phi(t)] \tag{II.1}$$

where A is the signal magnitude, $C_I(t)$ and $C_Q(t)$ are the in-phase and quadraphase components of the signal envelope, ω_O is the carrier (IF) frequency, $\Delta\omega_i$ is the ith hop frequency (which may be always 0 if not a frequency hopped signal) and $\phi(t)$ is the phase modulation of the carrier, which may or may not be constant. Furthermore, the $\Delta\omega_i$, the envelope and the phase modulation are always within the bandwidth B of the signal about the carrier frequency. This representation is general enough to represent most kinds of communication or navigation system transmissions, including JTIDS and GPS.

The bandwidth limited ambient noise can be represented as[2]

$$n(t) = x(t)\cos \omega_O t - y(t)\sin \omega_O t \tag{II.2}$$

where x(t) and y(t) are in-phase and quadraphase components of the noise with noise bandwidth B, which have Gaussian probability distributions and are statistically independent. That is,

$$E[x(t)y(t)] = 0 \tag{II.3}$$

Furthermore,

$$E[x^2(t)] = E[y^2(t)] = N = N_O B \tag{II.4}$$

where $\frac{N_O}{2}$ is the two-sided spectral density of the ambient noise.

The squaring process produces upper and lower sidebands at twice the IF frequency and at DC. The DC component is obtained by low-pass filtering the resulting squared signal plus noise, yielding

$$s_f^2(t) + n_f^2(t) = \frac{A^2}{2}[C_I^2(t) + C_Q^2(t)] + \frac{1}{2}[x^2(t) + y^2(t)] \tag{II.5}$$

The effect is that the bandwidth of the resulting signal component collapses to the bandwidth of the sum-squared in-phase and quadraphase modulation. The noise, although sum-squared, is still random. In the case of GPS and other BPSK or QPSK modulated signals, the sum-squared signal bandwidth is zero, resulting in a DC signal whose amplitude $\frac{A^2}{2}$ varies only with the received signal power. In the case of JTIDS and other MSK or Staggered-QPSK (SQPSK) modulated signals, the $C_I^2(t) + C_Q^2(t)$ becomes a pair of known frequency FSK tones that an interceptor can detect from the energy passed through a narrow band filter at those frequencies. On JTIDS, the tones are at ±1.25 MHz. But the net result is the same. In JTIDS, for example, the signal is still pulse modulated, but all resulting pulses are those tones. Without performing an extensive investigation, the same effect probably exists using other modulation schemes. The filtered-squared noise now has a Rayleigh or Chi-Squared probability density, while the filtered-squared signal-plus-noise has a Rician probability density. At this point, however, in spread spectrum systems, the noise usually strongly dominates the signal, unless the observer is close to the transmitter.

The authorized user has the capability of despreading the signal to a narrower bandwidth. This has the effect of bringing the signal above the noise, allowing the user to detect the signal and obtain the signal information. This despreading process does not require squaring, thus the filtered spread noise (and interference) has a Gaussian

---

[2]Mischa Schwartz, Information Transmission, Modulation and Noise, Fourth Edition, McGraw-Hill, 1990, pp.464 - 470.

probability density. However, the detection process requires some sort of squaring, which again results in the noise having a Rayleigh or Chi-Squared probability density, but with a much narrower bandwidth.

II.2.2 Signal-Plus-Noise and Noise Statistics The effect of the post-detection integration is then that the filtered-squared signal integrates linearly with time, while the integration has a smoothing effect on the filtered-squared noise. In the case of the interceptor, the integration time T_I will be quite long with respect to the inverse of the predetection bandwidth B. Because of this and the central limit theorem, the integrated filtered-squared noise now has a Gaussian probability density. Thus, it suffices to use this assumption in the probability of detection analysis. This is not the case, however, for the authorized user, especially if very low false alarm rates are required. The integration time T_I won't usually be long enough to make that assumption. Thus, the resulting probability density of the noise in this case is Chi-Squared with 2K degrees of freedom, where K is the ratio of the predetection and post-detection bandwidths. The probability density of the signal-plus-noise is unnamed and involves higher order Bessell functions for evaluation.

The detection criteria is a hypothesis test based on the probability distribution of no signal present versus that with a signal present. Because the Gaussian assumption can be made in the interceptor case, these probability densities can be defined in terms of the mean and variance of noise only and the mean and variance of signal-plus-noise. The mean and variance of the noise only case, independent of the probability of density, are

$$\mu_n = N_O B^2 T_I \tag{II.6}$$

and

$$\sigma_n^2 = N_O^2 B^3 T_I \tag{II.7}$$

respectively. For the case of signal-plus-noise, the mean and variance are

$$\mu_{s+n} = N_O B^2 T_I \left[\frac{S}{N_O B} + 1 \right] \tag{II.8}$$

and

$$\sigma_{s+n}^2 = N_O^2 B^3 T_I \left[2\frac{S}{N_O B} + 1 \right] \tag{II.9}$$

respectively.

Given a mean μ and variance σ^2, the Gaussian probability density is

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}} \tag{II.10}$$

II.2.3 Determination of Threshold TH The decision threshold TH is determined for a desired false alarm rate p_f, which is given as

$$p_f = \int_{-\infty}^{TH} p(x|n)\, dx \tag{II.11}$$

where $p(x|n)$ is Equation II.10 evaluated with the noise only statistics, or the appropriate probability density function in the case of the authorized user. Equation II.11 is solved for TH either iteratively, via standard library functions or via table look-up.

II.2.4 Determining the Probability of Detection Once TH has been determined, the probability of detection can be determined as a function of $\frac{S}{N_o}$ from

$$p_d = 1 - p_m \qquad (II.12)$$

where the miss probability p_m is determined from

$$p_m = \int_{-\infty}^{TH} p(x|s+n)\, dx \qquad (II.13)$$

where $p(x|s+n)$ is Equation II.10 evaluated with the signal-plus-noise statistics, or the appropriate probability density function in the case of the authorized user.

II.2.5 Decision Signal-to-Noise Ratio Evaluating the detection probabilities for a given set of communication system parameters can be quite cumbersome using the above equations. An alternative is a "rule-of-thumb" closed-form equation called the "Decision Signal-to-Noise Ratio". This equation provides a measure of the "distance" between the noise and signal-plus-noise probability densities based on the statitistics given above in Equations II.6, II.7, II.8 and II.9. The Decision Signal-to-Noise Ratio is given as

$$R_D = \frac{(\mu_{s+n} - \mu_n)^2}{\sigma_n \sigma_{s+n}} = \frac{\left[\frac{S}{N_o}\right]^2 \frac{T_I}{B}}{\sqrt{2\frac{S}{N_oB} + 1}} \qquad (II.14)$$

The term $\sqrt{2\frac{S}{N_oB} + 1}$ in the denominator is only significant for the authorized user who is despreading the signal and operating with a relatively narrow bandwidth B. For the unauthorized interceptor, B is large and the term is approximately 1 and can be neglected. Note that if this is true, this ratio is inversely proportional to the signal's noise bandwidth and directly proportional to the post-detection integration interval, which is to be expected. This equation can be expanded further to be expressed in dB and to include other signal parameters such as peak transmission power (P_{PK}), pulse duty cycle (PDC), carrier frequency (f_o) and the distance from the transmitter (d). The result is

$$SNR_D = 20 \log_{10} \left(\frac{\frac{P_{PK}\, PDC}{N_o} \left[\frac{c}{4\pi f_o d}\right]^2 \sqrt{\frac{T_I}{B}}}{\left[2\frac{S}{N_oB} + 1\right]^{0.25}} \right) \qquad (II.15)$$

where c is the speed of light in units per second for whatever the units of d are (=161875 NM/second if d is in NM), and N_o is the ambient noise density in watts/Hz based on the receiving system's noise temperature. Note that the effect of distance is the fourth power of the effect of predetection bandwidth B. That is why the effect of this parameter on LPI is limited at UHF and L-Band frequencies.

It is also interesting to note the effect of the pulse duty cycle. That effect must be clarified. If an authorized user knows the pulse pattern and correlates with that pattern in his acquisition process, the PDC in the equation should be set to 1, provided that he blanks the noise between the assumed pulse intervals in his processing. However, the post-detection integration interval T_I must then reflect that blanking, since integration only occurs over the supposed pulse intervals. Thus, the effect of PDC is the square root of what is shown in the equation. If he doesn't perform this process, and integrates continuously over T_I, the equation holds as shown.

The assumption here is that the pulse pattern is encrypted and the interceptor doesn't know the pulse pattern. Thus, the equation stands as written for the interceptor. Thus, the transmission of pulses in an encrypted pseudorandom pattern is obviously another LPI technique. Then, the pulse duty cycle has the same effect as T_I and the inverse of B.

In the case of JTIDS, for example, the pulse pattern is not pseudorandom, although the starting time of the pattern is jittered from one message to the next. Thus, in effect, the PDC is 1 for both the user and the interceptor, although, in both cases, T_I should reflect PDC. Thus, the pulsing provides no advantage to the user except that the interceptor's receiver would be more complex to account for it in reducing his T_I and correlating to the pulse pattern.

THIS PAGE INTENTIONALLY LEFT BLANK

II.3 Example Computations

An existing computer program that computes the probability of detection given a specified false alarm rate was modified to compute the probabilities of detection described above, along with the corresponding Decision Signal-to-Noise Ratio SNR_D. This modified program was used to determine the SNR_D required for various cases. Example computations using the JTIDS as an example are presented here.

The JTIDS transmitted message, with a signal structure described in Appendix III, has the following parameters: P_{PK} is 200 watts, f_0 is taken to be 1206 MHz and B is 153 MHz. Two cases are presented. In one, it is assumed that the interceptor correlates to the pulse pattern. In the other, it is assumed that the interceptor integrates over an entire message slot. In the correlating case, PDC is 1 and T_I is 258 x 6.4 μseconds = 0.0016512 seconds. In the non-correlating case, PDC is 0.0016512 $\div$ 0.0078125 = 0.21135 and T_I is 0.0078125 seconds. The former case is where the interceptor, knowing that the JTIDS signal has 258 equally spaced pulses that occur every 13 μseconds, correlates to that pulse pattern. In both cases, a noise figure of 3 dB, a cable loss of 1 dB and an implementation loss of 2.5 dB were assumed for the interceptors receiver.

Both the probability of detection and the Decision Signal-to-Noise Ratio are evaluated versus distance from the transmitter for the two PDCs and PDIs. The results are shown in Figures II.2 and II.3. The probability of a false alarm (p_f) is taken to be a modest 0.001. Note that both cases be detected with a high probability at <u>over 500 NM</u>. This distance is larger than the advertised range of JTIDS, but mainly because of the AJ margin factored into the system. Besides, detecting at large ranges is meaningless because it is beyond the radio horizon for L-Band signals. We must also consider detection from a satellite observer. The definition of LPI that we are deriving later is based on a ratio of distances anyway, since it is recognized that the signal levels could be decreased with modifications. This does emphasize, however, the need for other LPI techniques, such as pseudorandom transmission, jitter, variable power transmission and "spotlighting," which were suggested in the Tentative Operational Requirements (TOR) for Sea-Based TACAN Replacement.

The results also show, at least for the case of JTIDS, that the correlation to the known pulse pattern allows detection at about 1.5 times the distance than simply detecting "a" signal in a known 7.8125 millisecond time slot. However, that is misleading, because the equipment required to correlate to the pulse pattern is much more complicated than equipment designed to detect only the presence of the signal, but not by much.

Comparing the plots of p_d and SNR_D show that the Detection Signal-to-Noise Ratio can be used as a "rule-of-thumb" evaluation criteria. For both PDIs, p_d dropped below 0.9 at the 12.8 dB level of SNR_D. This is not only the case for this example, but is usually true for the case where the false alarm rate is 0.001 and the probability of detection is 0.9. Thus, the probabilities don't have to be evaluated as a criteria for determining the LPI capability of a data link.

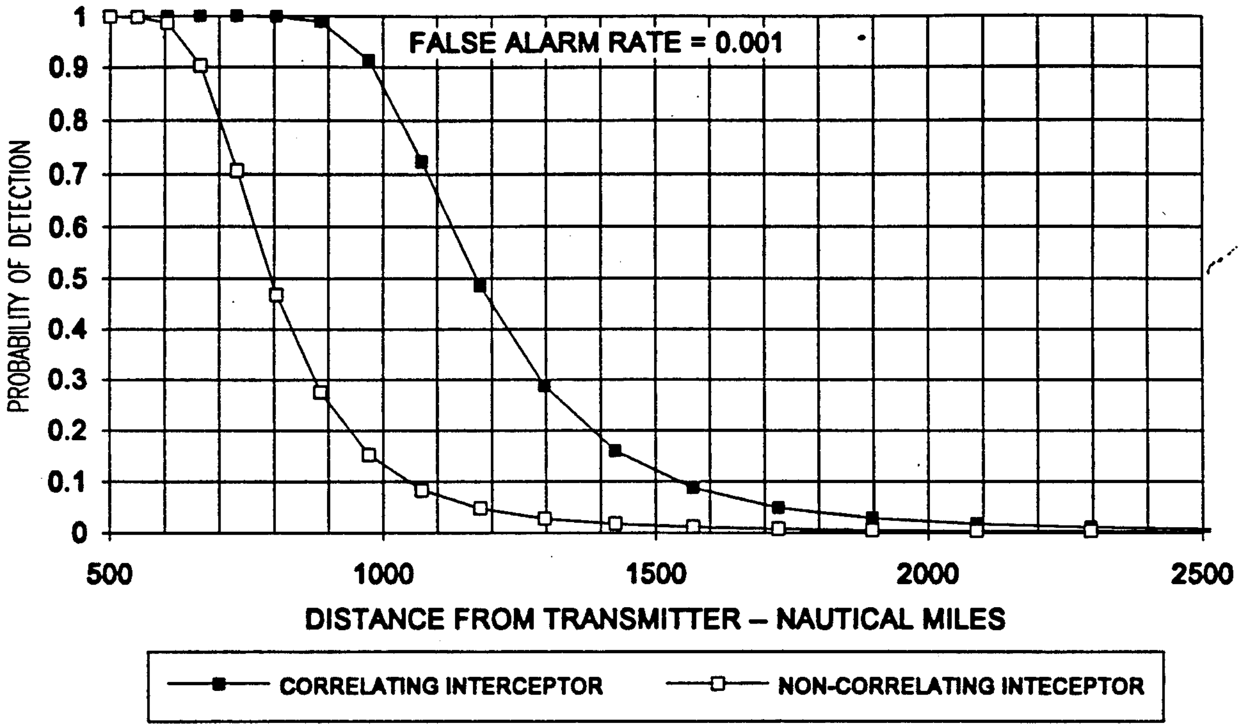

Figure II.2 Probability of Detection of Signal for Interceptor for JTIDS Example

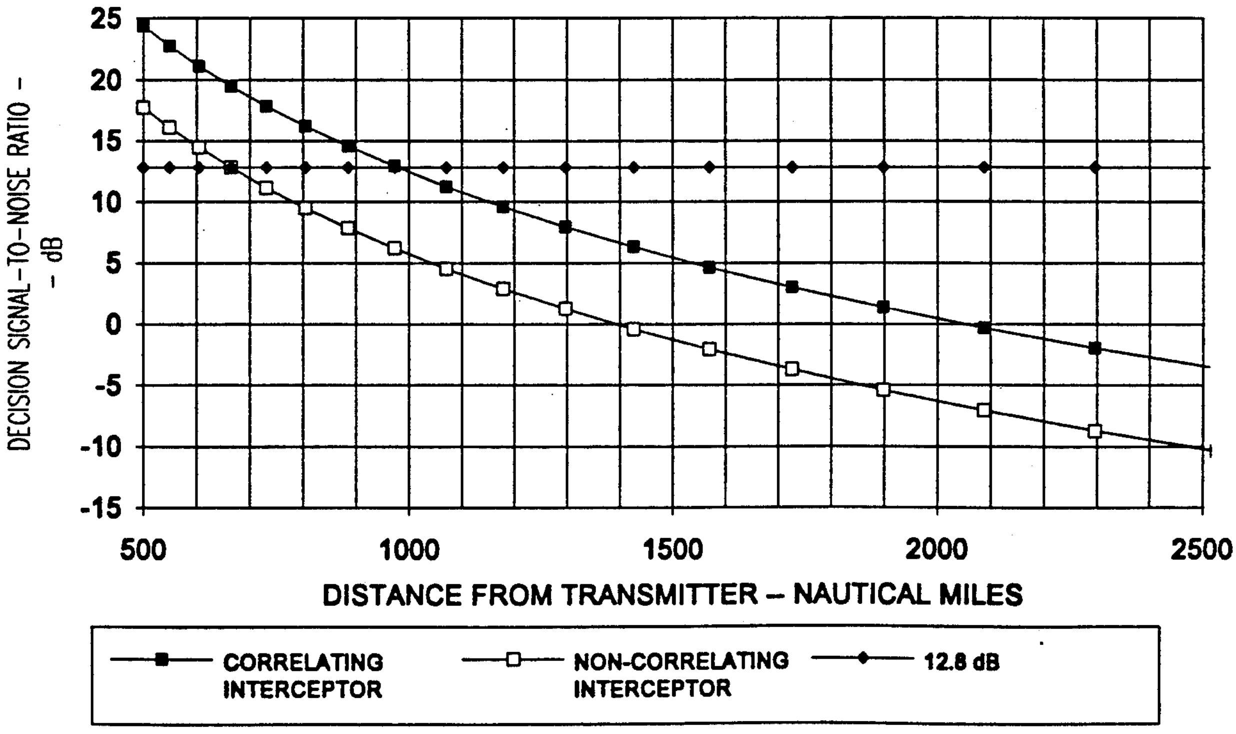

Figure II.3 Decision Signal-to-Noise Ratios for Interceptor for JTIDS Example

II.4 General LPI Requirements

Equation II.14 also applies to the authorized user of the data link, except some parameters take on different meanings. Generally, acquisition of a transmitted message is the most difficult for the authorized user. Thus, let us evaluate that case. That is, let R_{DU} be the Decision Signal-to-Noise Ratio required for acquisition by the user at the range of operation d_U, and the user's acquisition noise bandwidth $B = B_U$. B_U is usually much narrower than the interceptor's B_i because of the authorized user's knowledge of the spread spectrum spreading codes. T_I here is the user's PDI T_U used for acquisition. The rest of the parameters in that equation should be equal for both the authorized user and the intercepting observer, with the exception of receiver design dependent parameters such as noise figure, cable loss and implementation losses which affect the received signal-to-noise density. Also, as described above, the duty cycle for the interceptor may be different than that of the user, depending upon pulse pattern correlation.

The average transmitted signal-to-noise density, which is given by

$$\frac{S}{N_{Oi}} = \frac{P_{PK}\,PDC_i}{N_{Oi}} \tag{II.16}$$

as seen by the interceptor, and

$$\frac{S}{N_{OU}} = \frac{P_{PK}\,PDC_U}{N_{OU}} \tag{II.17}$$

as seen by the user, where the noise density for either case is given in dB/Hz as

$$N_O = 10\log_{10} KT + NF + L + IL \tag{II.18}$$

where NF is the noise figure, L is cable loss and IL is implementation loss, which may be different for the interceptor and the user.

R_{DU} can be different for the user from th R_{Di} for the interceptor. The authorized user must be sure that he acquires the message. The observer usually would have another try at it with other transmitted messages. For example, the JTIDS terminal (see Appendix III) is designed to have a very low false alarm probability and a very high probability of detection. It is shown in that appendix (Figure III.11) that this requires an SNR_D of 18.5 dB. This is 5.7 dB more than that required for an interceptor with a moderated false alarm probability of 0.001 and a probability of detection of 0.9.

By evaluating Equation II.14 for both the authorized user and the observer and combining them yields the expression

$$\frac{d_U}{d_i} = \left[\left(\frac{\dfrac{PDC_U}{N_{OU}}}{\dfrac{PDC_i}{N_{Oi}}} \right)^2 \left(\frac{\dfrac{T_U\,B_i\,R_{Di}}{T_i\,B_U\,R_{DU}}}{\sqrt{2\,SNR_{Ur}+1}} \right) \right]^{\frac{1}{4}} \tag{II.19}$$

where the noise densities are as defined in Equations II.16, II.17 and II.18, and the radical in the denominator of Equation II.14 is approximately unity for the interceptor. SNR_{Ur} is the user-required signal-to-noise ratio to achieve the user's probabilities of false alarm and detection, where

$$SNR_{ur} = \frac{S}{N_o}\frac{1}{B_u} \tag{II.20}$$

is determined in conjunction with R_{DU} for a given set a probabilities and system parameters. For example, for the JTIDS parameters, its value is 4 dB (15 dB required less the noncoherent gain of 11 dB). Thus, the value under the radical is approximately 6, resulting in a factor of 0.8 applied to the distance ratio. Note that there is no dependence on transmitted power in Equation II.19, only dependence on required signal-to-noise ratios of each system to obtain the desired probabilities.

Using various parameters from the JTIDS interceptor examples of Section II.3 of this appendix and Section III.4.2.2 of Appendix III in Equation III.19 yields remarkably consistent results. However, it should, since the Decision Signal-to-Noise Ratios used were derived from the same parameters. However, since those ratios seem to be fixed once established for the given system bandwidths, Equation III.19 can be used for a variety of parameters such as interceptor integration times and receiver losses of both the interceptor and user.

II.5 LPI Requirements Summary

There is a difference between Low Probability of Exploitation (LPE), Low Probability of Intercept (LPI) and Low Probability of Detection. LPD is the capability to prevent detection of one's existence by an observer. LPI is the capability to prevent one's identification by and observer. LPE is the capability to prevent determination of one's location or to prevent the interception of the information being transmitted. For the purpose of this study, LPI and LPD are considered one and the same.

The prevention of the interception of the information being transmitted is the straight-forward application of signal and data encryption. The prevention of detection of one's existence by an observer or the determination of one's location by an observer are similar. They both require the observer to monitor signal transmission. The wider the transmission bandwidth and the shorter the messages are, the more difficult it is for the observer to perform either of these functions. However, the authorized user must receive a finite amount of signal energy to acquire the signal and read the message. Thus, the intercept observer also can perform his function at some distance from the transmitter. The best we can hope for is to make it as difficult as possible for him to perform his function.

II.5.1 Spread Spectrum Requirements Spread spectrum communications is a step in the right direction for LPI because it widens the transmission bandwidth. Encrypting the codes used to spread the signal causes the interceptor to monitor the entire spread spectrum bandwidth so as to receive the full power of the transmission. Thus, the processing gain of the decoding process gives the user the advantage. However, the user must be much more precise and error free in his reception. The interceptor is only trying to detect existence. He can usually afford to make an occasional mistake in his detection process. Thus, the interceptor gains back some advantage.

To gain a significant advantage using spread spectrum techniques for LPI, it is necessary to operate at a relatively high frequency so as to gain a significant bandwidth advantage. A formula was derived (Equation II.19) that relates the ratio of the useful distance of the user to the interceptor based on signal parameters, including bandwidth. This equation shows that this ratio is proportional to the fourth root of processing gain, emphasizing the requirement for a relatively wide bandwidth. At frequencies where economical receivers/transmitters can operate, this bandwidth is somewhat limited. Thus, techniques other than the use of spread spectrum communications are required for effective LPI.

II.5.2 The Requirement for Other LPI Techniques Because of the limited effectiveness of spread spectrum bandwidth, especially for operations at the UHF and L Band frequencies where bandwidth is a premium, other LPI techniques are required. Overall, these techniques were suggested in the Tentative Operation Requirements for Sea-Based TACAN Replacement, namely "Transmitter operation should be variable from a maximum hemispherical distance of at least 300 NM to graduated range reductions with a 'spotlight' aim capability in azimuth, elevation, base height and ceiling height with fixed, rotational, random, raster or jitter illumination to enhance LPI qualities."

The "spotlight" capability obviously reduces detectability in areas not spotlighted. Jitter illumination, a capability that JTIDS has, makes it more difficult for the interceptor to obtain "correlation" with a fixed pulse pattern. Jitter, here, causes the start times of successive transmitted messages to be pseudorandom according to some encryption algorithm that the authorized user knows.

Other capabilities that are useful are:

1) Pseudorandom burst communications to prevent the observer from anticipating transmission and using sweeping antennas to learn the bearing to the transmitter. This does not include a "pulsed" signal structure.

2) If a "pulsed" signal structure is used, the timing of the pulses should be pseudorandom according to some encryption algorithm, so that the observer cannot correlate to the pulse pattern, reducing his chances to detect the "full" power of the signal. Usually, a "pulsed" signal structure is for technical convenience, a random pulse pattern can be useful for LPI. For example, JTIDS is pulsed to reduce interference to TACAN. Likewise, the proposed pseudolite signal presented in Appendix IV is pulsed to reduce interference to the reception of the GPS satellite signals. Unfortunately, the JTIDS pulsing is uniform. Thus, it allows the interceptor to "correlate" to the pulse pattern. The pulsing in the proposed pseudolite signal structure is

pseudorandom. The pulsing in the proposed LPI data link of Section 2.2.7 of this report is also pseudorandom.

3) Reduce the transmitted power when necessary, or when the range capability of the system can be reduced. Obviously, the range of the intercept observer also will be reduced.

In 3), Equation II.19 still holds. Only the effective range is reduced.

If possible, all these techniques should be included in the requirements for a data link to support the Shipboard TACAN Replacement.

APPENDIX III

JOINT TACTICAL INFORMATION DISTRIBUTION SYSTEM (JTIDS) DESCRIPTION

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

III.1.0 The JTIDS Signal Structure

An overview of the JTIDS system is described in a MITRE report.[1] This report describes the JTIDS signal structure at a high level, but does not provide details sufficient enough to assess whether or not it meets, or can be modified to meet, the requirements for the subject data link. More details were obtain from Hughes Aircraft Company Ground Systems Group.[2] The following is a detailed summary of the JTIDS signal structure from those two documents as it pertains to this study.

III.1.1 Operational Overview JTIDS is an information distribution system that can distribute data in either a broadcast mode or point-to-point communications, using a system architecture based upon a Time Division Multiple Access (TDMA) design. It operates as a nodeless network in that messages need not pass through a node to be distributed. Any participant can transmit a message directly to any other participant by simply transmitting in a assigned time slot. However, a designated terminal, called a Net Time Reference (NTR), will act as the time reference for either all the networks or for individual networks. Up to 128 such networks can be set up at a time in a given area. Details on how time slots and networks are set up are presented later.

As applied to the distribution of DGPS messages, JTIDS would operate in a broadcast mode, where each ship would broadcast its position, etc., in either assigned time slots, all within a given network, or in assigned time slots on a different network, or a combination of the two. How this would be done would have to fit within the structure of how JTIDS is used for other applications. If the DGPS capability were extended to include air-to-air range and bearing, the two airborne JTIDS terminals would operate in a point-to-point communications mode.

There are 128 time slots per second per network for a total of 98,304 time slots per network per 12.8 minute system epoch. Time slots are assigned in a system epoch period. As little as one time slot can be assigned. Each time slot is 7.8125 milliseconds long and is divided into a variable start time (jitter), a synchronization preamble, the information message and a propagation time period. The propagation time provides propagation to a normal range of 300 nm before an new time slot starts, thus satisfying the Shipboard TACAN replacement requirement for a 300 nm range. Without jitter, the propagation range is 500 nm.

The system is also capable of digital voice transmission, which could be used for air traffic control.

III.1.2 Frequency Allocation JTIDS operates in the L Band frequency range of 960 to 1215 MHz, which also includes the frequency allocations for IFF (Identification, Friend or Foe), DME and TACAN. In order to not interfere with IFF, JTIDS does not transmit in the bands of 1008 to 1053 MHz and 1065 to 1113 MHz. In the case of TACAN and DME, JTIDS operates on an non-interference basis. Since the frequency band is used for air navigation, during peace time JTIDS has been authorized to operate without prior coordination at a system level of 40% of capacity, and at a terminal level of 20% of capacity. Hughes Aircraft Company indicated that JTIDS has not yet received permanent allocation authorization.

This authorization problem may not be a problem if TACAN is phased out and for the use of JTIDS for broadcasting DGPS corrections because DGPS is an air navigation application.

III.1.3 Signal Power The standard transmitted peak RF power of a JTIDS Class 2 fighter terminal is 200 watts (53 dBm) (Effective Radiated Power - ERP). Some terminals have higher power capability for a burn-through mode in case of heavy jamming. However, for the purpose of this study, the 200 watt number will be assumed. The received signal power through a 0 dBic gain antenna of a terminal is then

$$P_r = 53 + 20 \log_{10} \left[\frac{\lambda}{4\pi d} \right] \text{ dBm} \qquad \text{(III.1)}$$

[1]TDMA JTIDS Overview Description, MITRE Report No. MTR8413, Revision 1, dated May 1984.

[2]Hughes Aircraft Company Proprietary Presentation titled "JTIDS Principles", dated 11 January 1988.

where λ is the signal carrier wavelength and d is the distance from the transmitter in the same units. In terms of nautical miles (nm), the worst case wavelength for the frequency band is

$$\lambda = \frac{161875 \text{ nm/sec}}{1206000000 \text{ Hz}} = 0.000134225 \text{ nm} \tag{III.2}$$

so that the received power for d in nm is

$$P_r = -46.43 - 20 \log_{10} d \text{ dBm} \tag{III.3}$$

At a distance of 300 nm, the received peak power is approximately -96 dBm. Thermal noise power in the transmission bandwidth is approximately -86.25 dBm as a comparison, assuming a receiver system noise figure of 4 dB.

III.1.4 Signal Structure The allocation, excluding the bands reserved for IFF, allows for system operation in a 153 MHz bandwidth. The basic spread spectrum technique used in JTIDS is that of Frequency Hopping, Thus, this 153 MHz bandwidth is broken up int 51 frequencies spaced 3 MHz apart, which are used as frequency hopping channels. Each hop has a 6.4 μsecond duration, separated by a 6.6 μsecond dead time when transmission does not occur and frequency switching takes place. Thus, the transmission is a pulsed transmission, where each pulse is at a different frequency of 51 possible frequencies, with a pulse duty cycle during transmission of 49.23%, as is illustrated in Figure III.1. This does not include the fact that transmission does not occur during the start time (jitter) period or the propagation time period, resulting in a message duration of approximately 3.354 milliseconds in a 7.8125 millisecond time slot. There will be more discussion of these times later. The sequence of frequencies is pseudorandom and encrypted, providing both jamming resistance and a low probability of intercept. Each message (time slot) consists of 258 pulses.

Each pulse has a 3 MHz bandwidth, since the carrier at the hop frequency transmitted at that time is modulated with a 32 bit code with a clocking rate of 5 MHz. The modulation technique is called Continuous Phase Shift Modulation (CPSM), usually referred to as Minimum Shift Keying (MSK).[3] Essentially, MSK is a spectrally efficient modulation technique where the 5 MHz code can be transmitted in the allotted 3 MHz bandwidth. It differs from the bi-phase-shift-keying (BPSK) technique used on GPS in that the phase transitions are applied gradually using sinusoidal modulation, thus, reducing the power in the high frequency components of the modulated signal. This spectrally efficiency does not come for free, however, because the modulation-demodulation implementation is more complicated than that for BPSK. The modulation technique used on JTIDS is very similar to PSK, using a PSK modulator with a SAW filter to achieve CPSM. The demodulation technique is in-phase (I) and quadraphase (Q) PSK versus in-phase demodulation using BPSK.

The 32 bit code represents one of 32 possibilities of a 5 bit symbol. It is actually a single 32 bit sequence (encrypted) shifted by one bit for each of the 32 bit possibilities, where the sequence 01111100111010010000101011101100 represents the symbol 00000. This sequence is barrel-rotated 1 bit to the left to represent the symbol 00001, etc. These symbols are called that as they represent the data bits represented by one 6.4 μsecond pulse $\left(\frac{32}{5000000} \text{ seconds}\right)$. In effect, the message is not made up of symbols (such as characters), but made up of a string of bits that is a concatenation of multiple 5 bit symbols. In one message structure option, the 5 same bit symbol is re-transmitted to form a double pulse transmission to improve the AJ margin. The symbols are PN coded before transmission.

III.1.5 Message Structures The JTIDS message structure for four different message types are illustrated in Figure III.2. The message types differ in two ways. The first two types illustrated include a jitter start time at the beginning of the 7.8125 ms time slot, which is an encrypted random time to provide additional AJ margin and protection against exploitation. However, this additional margin is minimal and steals half of the data capacity. Details about

---

[3]For a detailed description of MSK, see James J. Spilker, Jr., Digital Communications by Satellite, Prentice Hall, 1977, pp. 313 - 324, or Mischa Schwartz, Information Transmission, Modulation and Noise, Fourth Edition, McGrall-Hill, 1990, pp. 231 - 236.

this jitter time are classified. It is more efficient to use double pulses to gain additional AJ margin (2.2 dB) than to use the jitter time. The jitter time could also help defeat an "interceptor" from knowing exactly when a possible message is being transmitted. This either causes him to "average" over the entire time slot, or prevents him from ranging on the time of reception. The jitter also minimizes the ability of a pulse jammer to synchronize to the received pulses.

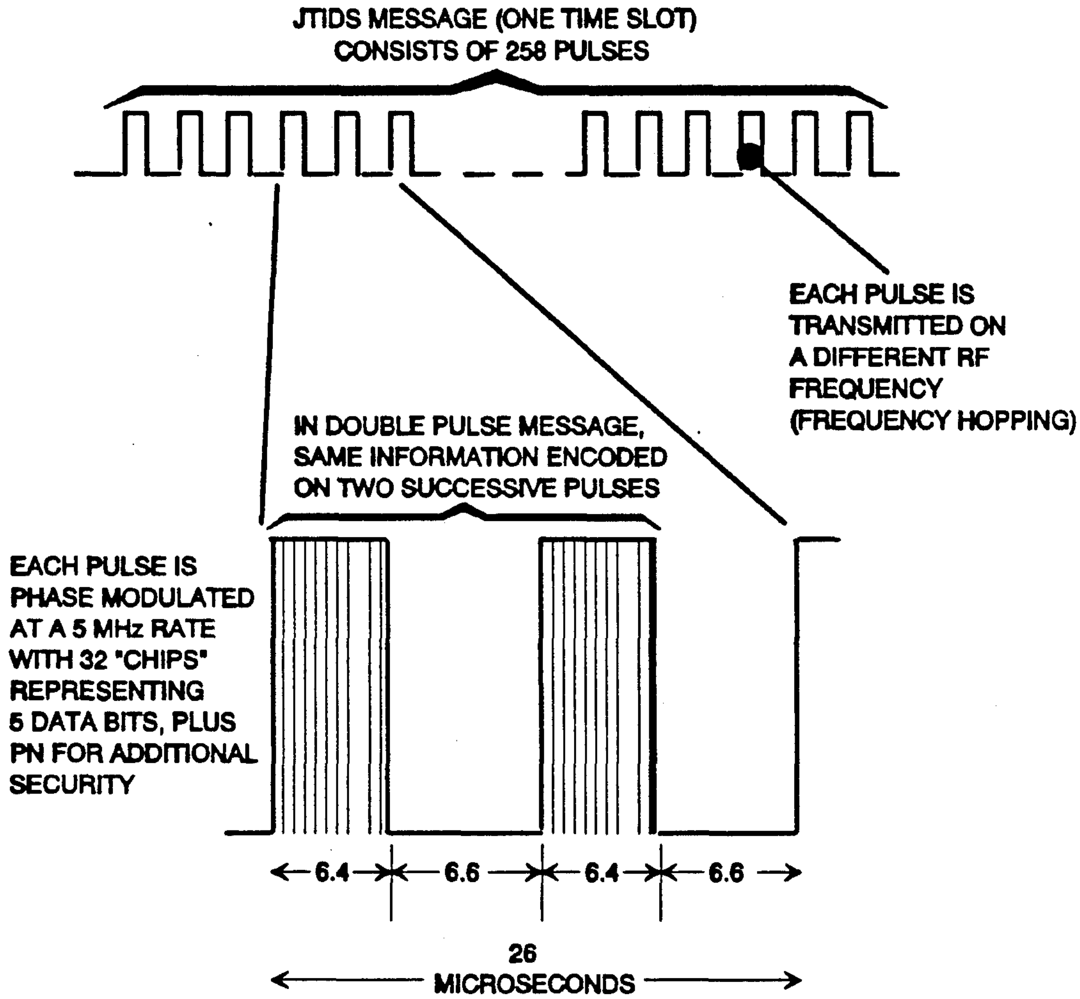

Figure III.1. JTIDS Pulsed Waveform

The second way the message types differ is in the use of single or double pulses per 5 bit symbol. Double pulses provide an additional 2.2 dB of AJ margin at the expense of cutting the data capacity by one half. The additional AJ margin is achieved by a non-coherent adding of the symbols to increase the signal-to-noise ratio. Coherent adding of the symbols is not possible because they are received on different frequencies. Double pulses also provide diversity to minimize multipath effects.

During the Sync period, the transmitter transmits 16 double pulses, or 32 pulses total, each of which consist of the 32 chip code representing the 5 bit 00000 symbol. During this period, the frequency hopping only uses 8 of the 51 possible frequencies, transmitting 4 pulses on each of the 8 frequencies. The 8 frequencies and the corresponding time of the pulses are encrypted, so they are not known to the unauthorized interceptor. The purpose of the Sync period is for the receiver to sync to the pulses, since the user usually doesn't know the range to the transmitter, nor does he always know time, at least not initially. The implementation of this synchronization in the terminals is one of the cost drivers of the receiver implementation, since, in order to achieve the full AJ capability, all 8 frequencies must be received during the Sync period. Some (or all) aircraft installations have 2 antennas, one upper and one lower. In this case, 4 frequencies can be monitored on each antenna, reducing the

AJ margin by 2.2 dB, but possibly gaining it back since the jammer is likely to be visible from one antenna. Then, again, the transmitted signal may also be visible from one antenna, which may be the one which is being jammed. If this is the case, 2.2 dB margin is lost, while, in the case where the signal is received from the opposite antenna as the jammer, much margin is gained. Again, the 2.2 dB is due to non-coherent addition (or elimination) of pulse correlation power, rather than 3 dB, if coherent.

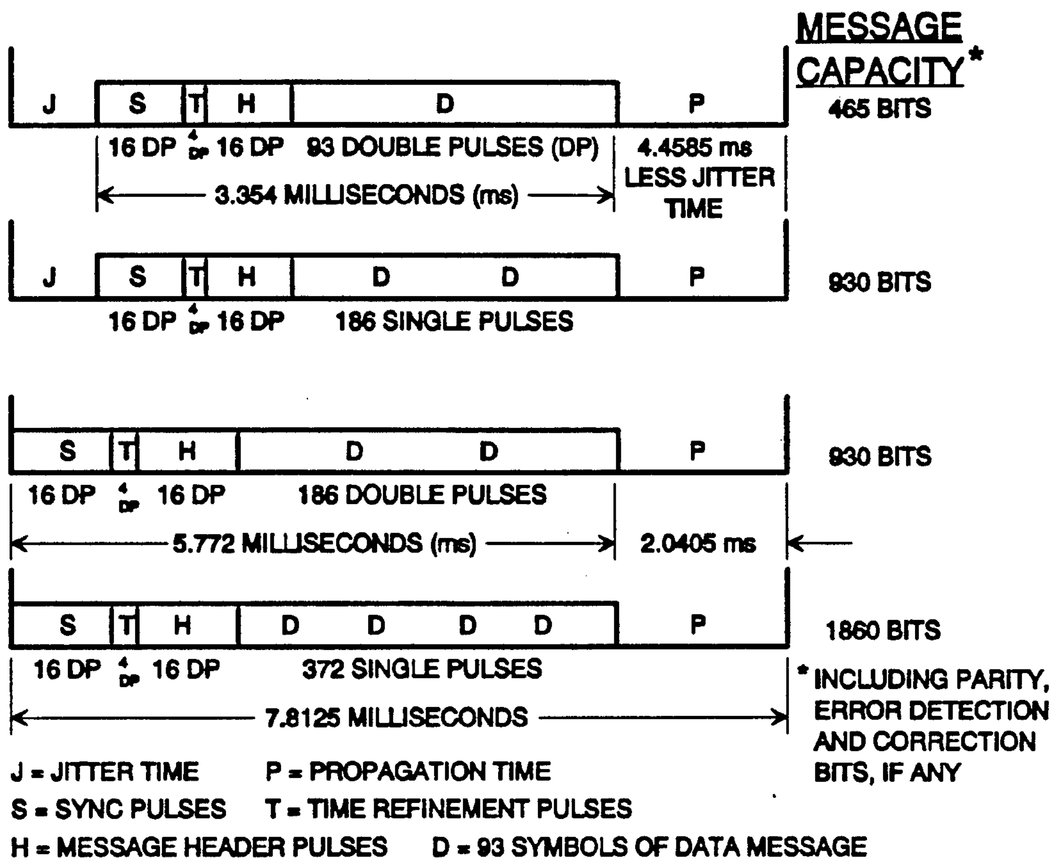

Figure III.2. JTIDS Message Structures

The dual antenna approach also accommodates the case where the terminal is communicating with participants at a higher altitude as well as participants at a lower altitude.

Some lower cost JTIDS terminals, such as for the US Marines, can only receive synchronization pulses on 2 frequencies, thus reducing the AJ margin by 6.6 dB with respect to the terminals that receive 8 frequencies. Loss due to multipath and fading are even greater.

At the end of the Sync period, as indicated in Figure III.2, a 4 double pulse period (104 μseconds) are transmitted for the purpose of time refinement to chip time after acquisition (chip synchronization). This time is similar to code and carrier pull-in in a GPS Receiver, whereas the synchronization period is similar to code acquisition in a GPS receiver. At the beginning of this time refinement period, the frequency hopping algorithm starts to use all 51 frequencies. Of course, the pattern of the "hops" is encrypted, but is known to authorized participants. The 32 bit code pattern is still the encrypted version of that representing a five bit 00000 symbol.

The time refinement period is followed the message which interleaves a header plus three Reed-Solomon words in a 16 double pulse period (80 bits in 416 μseconds). The purpose of the header is to provide the following:

1) type of message

2) source address of the originating terminal

3) security information to decode the message (Secure Data Unit serial number)

The rest of the message provides the message data. As seen in Figure III.2, the message data can contain either 465, 930 or 1860 bits, depending upon whether double or single pulses are used and whether or not a jitter period is used. Of these bits, 16 of every 31 are used for error correction using a Reed-Solomon code. (This error correction process will be described later.) Thus, the 465, 930 and 1860 bit message data becomes 225, 450 and 900 bit messages, respectively, which are subdivided into 3, 6, and 12 - 75 bit words, respectively, for the TADIL J message format, which is illustrated in Figure III.3.

Of the 5 parity bits in each word, one is a spare. The parity, which spans three words (12 bits), which provides error detection on the uncoded data that has passed the Reed-Solomon error correction process. Thus, the message must be made up of a multiple of 3 words to include this parity, even if dummy words need to be added (extension words).

The last two bits of each word indicate whether or not the word is the first of a message (initial word), a continuation word of a message, or, as indicated above, an extension word to fill out the message to complete the parity. Thus, the remaining data fields contain only 68 information bits, so that the message structures illustrated in Figure III.2 contain only 204, 408 and 816 information bits, respectively. These are the bottom line numbers for a 7.8125 ms time slot capacity, providing effective information rates of 26.112, 52.224 and 104.448 Kbits/second, respectively. Of course, these data rates are academic, since multiple time slots would be required to realize them. Messages can also be sent without Reed-Solomon coding for higher capacity.

III.1.6 Error Correction Error correction is accomplished using a Reed-Solomon forward error-correction code, which can recover partially corrupted data. The encoding process is illustrated in Figure III.4 for the 75 bit data words, which uses a (31,15) Reed-Solomon code. That is, for every 31 bits transmitted, only 15 contain data. The other 16 are code bits. Actually, the (31,15) represents symbols. Thus, the Reed-Solomon code operates on 155 bits at a time, encoding an entire 75 bit TADIL J word.

A JTIDS receiver has a Reed-Solomon decoder, which can output a correct data word if

$$E + 2e \leq 16 \qquad \text{(III.4)}$$

where E is the number of erasures and e is the number of symbol errors. An erasure is when a symbol can not be interpreted, where an error is when a symbol is interpreted wrong. For example, it may be impossible to interpret a 32 chip code sequence into any one of the 32 - 5 bit symbol possibilities, resulting in an erasure. A symbol error is one that is interpreted as a valid 32 - 5 bit symbol, but the wrong one.

The header, which consists of only 16 symbols, is encoded with a (16,7) Reed-Solomon code. Thus, the 16 double pulse symbols consist of only 35 bits of information. In this case,

$$E + 2e \leq 9 \qquad \text{(III.5)}$$

III.1.7 Symbol Interleaving and 32 Chip Cyclic Code Generation After the data and header symbols are encoded, they are interleaved to provide burst error protection, which also provides AJ resistance to pulse jamming. This is accomplished prior to concatenation with the 40 - Sync and Time Refinement symbols. Then, all 258 encrypted, encoded and interleaved pulse symbols are again encoded into corresponding 32 - chip cyclic codes. The resulting 32 - chip codes are then encrypted prior to signal modulation.

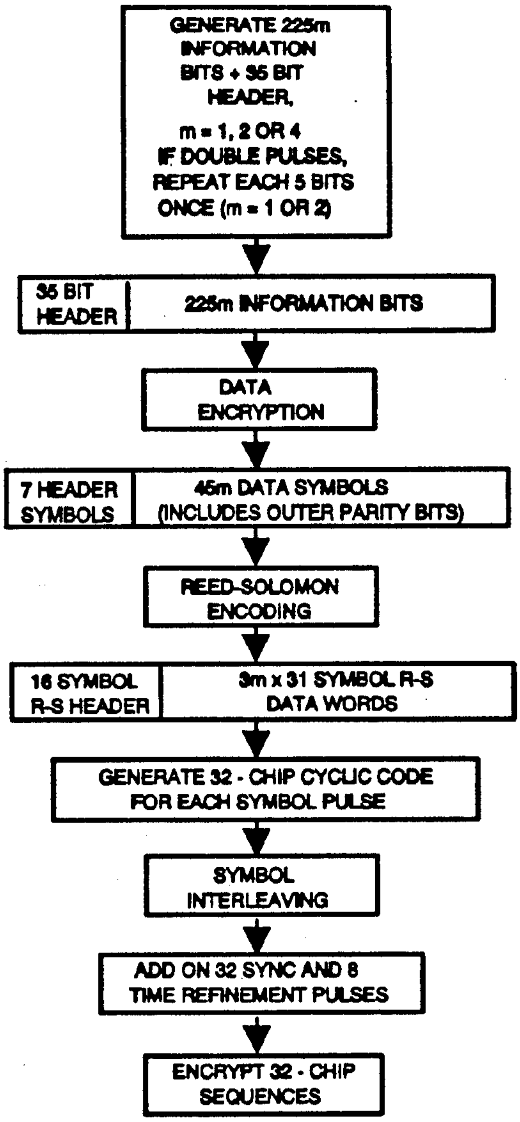

Figure III.3. JTIDS Message Generation Process

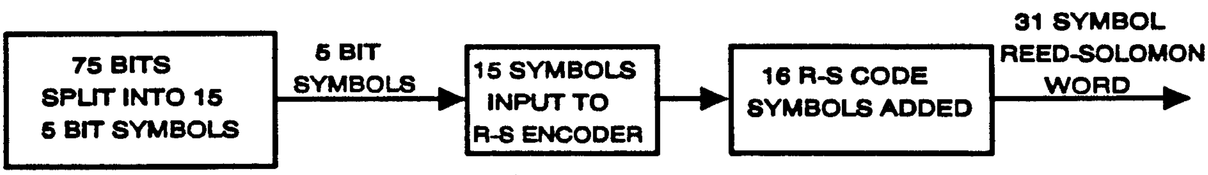

Figure III.4. Reed-Solomon Encoding Process

III.2.0 JTIDS Information Distribution[4]

JTIDS provides for a wide variety of information distribution techniques that can be configured by the user to match his particular needs. Information distribution is accomplished by the pooling of time slots into participation groups and the assignment of various net management time slot access modes to a group. Time slots are assigned in blocks of 2^n time slots. Here, only those protocols and access modes that appear to be applicable to the Shipboard TACAN replacement application will be described.

III.2.1 Distribution Structure The system can be organized to provide a broadcast receiver-oriented structure or a circuit-oriented structure. The broadcast receiver-oriented structure is the most applicable to the Shipboard TACAN replacement application. It is organized so that information (ship's location, heading, etc.) is broadcast without any specific addresses being identified. User's desiring information (ship's location, heading, etc.) contained in the broadcast group listen to the applicable time slots for that information. An aircraft may also broadcast its position, velocity, etc. in order to provide a air-to-air range and bearing. Platforms send position reports a minimum of once every 12 seconds called Precise Position Location Reports.

III.2.2 Access Mode The dedicated access mode is the most applicable to the Shipboard TACAN replacement application. In this access mode, specific time slots are assigned to a specific user (DGPS, in this case) and only this user transmits in the assigned time slots. Each ship with DGPS may be assigned a different set of time slots, or a set on a different network. Since DGPS information must be updated, the time slots must be distributed over time.

III.2.3 Voice Capability If the Shipboard TACAN replacement capability is expanded to include Air Traffic Control, a voice capability may be desirable. JTIDS provides for the transfer of digitized voice data. A bit stream resulting from the digitization of an audio signal is divided into time slot-size packets and transmitted in periodic time slots. At the receivers, the series of periodic time slots are received and recombined into the digitized voice bit stream, which is fed to the voice digitizer. The digitizer reconstitutes the audio signal.

---

[4]See TDMA JTIDS Overview Description, MITRE Report No. MTR8413, Revision 1, dated May 1984 for details.

THIS PAGE INTENTIONALLY LEFT BLANK

III.3.0 JTIDS Terminal Overview

As of May 1984,[5] there were four classes of US Air Force and Army JTIDS terminals. Each class supports a general grouping of users:

1) Command/Control Users (Class 1) is intended for use in large-scale airborne and surface command and control systems. This terminal is used on NATO E-3 aircraft and its corresponding ground entry points.

2) Small Platform Users (Class 2) is intended for use in aircraft and small, mobile command and control elements.

3) Missile/Manpack Users (Class 3) is intended for use in very small elements to include manpacks, missiles, transponders and voice only applications. This terminal was never built.

4) Army (Class 2M) used by the army, which is a 2 receiver terminal.

The US Navy has a Class 2 ship terminal, a Class 2 E2-C terminal and just the Class 2 terminals above for the other fighters.

Figure III.5 provides a functional configuration of a JTIDS terminal, while Figure III.6 provides a more detailed description. A short description of each function follows, based on the referenced documents and private communications with Hughes Aircraft Company personnel. The accuracy of the description that follows may not be the best, because information on the actual current day configurations is sketchy. According to Hughes, the Class 1 terminals were never put into production, being replaced with Class 2 terminals. However, there may be more than one Class 2 terminal per large-scale airborne or surface ship installation. The status of the Class 3 terminal is unknown.

III.3.1 Transceiver/Processor Unit The Transceiver/Processor Unit unique to the Hughes design, shown in Figure III.5 provides the transmission and reception, signal processing and communications processing functions of the terminal. It consists of the Transmitter/Exciter, Signal Processor and Communications Processor. The Transmitter/Exciter provides the signal modulation and demodulation of the JTIDS signal waveform. It normally consists of 2-8 receiver channels and contains up/down converters, frequency synthesizers and detectors, modulators and switching circuits. The Class 2 terminals have 8 receiver channels. The equivalent functions of the Transmitter/Exciter shown in Figure III.6 are the up-conversion, CPSM modulation, and reception. Part of the up-conversion function is the function of frequency hopping under the control of the Signal Processing function. The reception function performs filtering, frequency de-hopping, down-conversion and phase detection. The received message is digitized by the reception function for processing by the Signal Processing function. The shipboard applications have 2 or more terminals in order to transmit in more than one network at a time.

The Class 2 terminal has the Transmitter/Exciter-Receivers in the Receiver/Transmitter Unit. This unit interfaces with the Digital Data Processor at a non-hopped IF frequency of 75 MHz. The Class 2 performs synchronization acquisition and chip timing on the 32 pulse synchronization signal and doesn't utilize the time refinement (8) symbols.

The Signal Processor performs the preamble processing (synchronization and time refinement) and data message processing for both reception and transmission, including parity error detection, Reed-Solomon error correction coding and decoding, symbol interleaving and deinterleaving, CCSK encoding and decoding and RF frequency selection. It also controls the encryption and decryption of message data and the generation of the pseudonoise random sequences performed by the Secure Data Unit to establish data security and spread spectrum properties. The Signal Processor also contains the time-of-day clock that it uses is to aid in message synchronization and to control time of transmission in the time slot assigned.

[5] TDMA JTIDS Overview Description, MITRE Report No. MTR8413, Revision 1, May 1984.

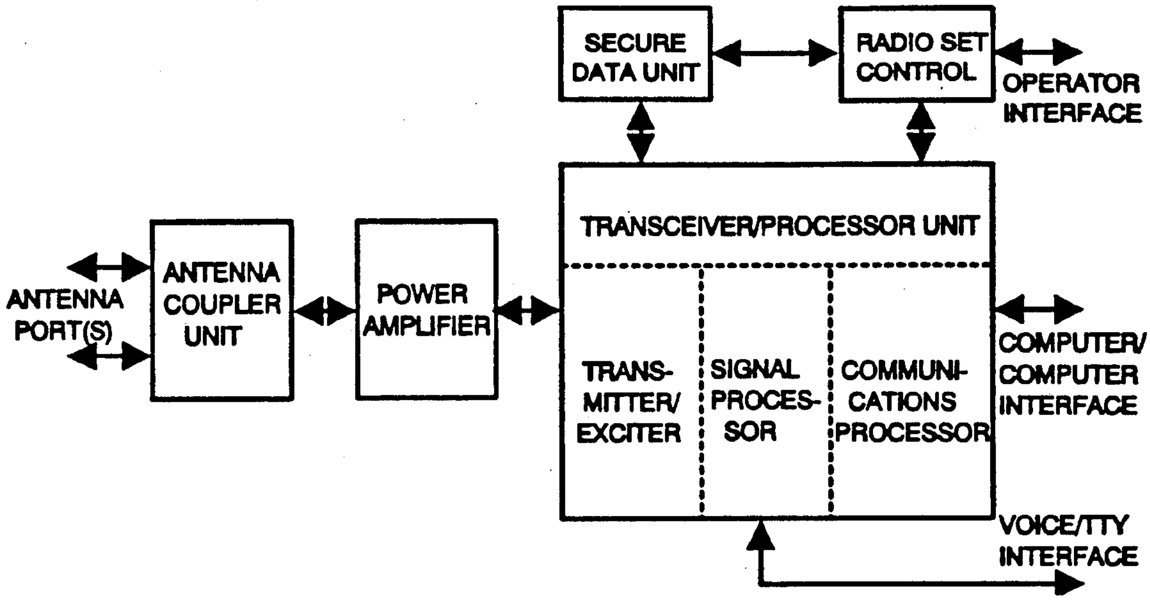

Figure III.5. Hughes Class 1 JTIDS Terminal Functional Configuration

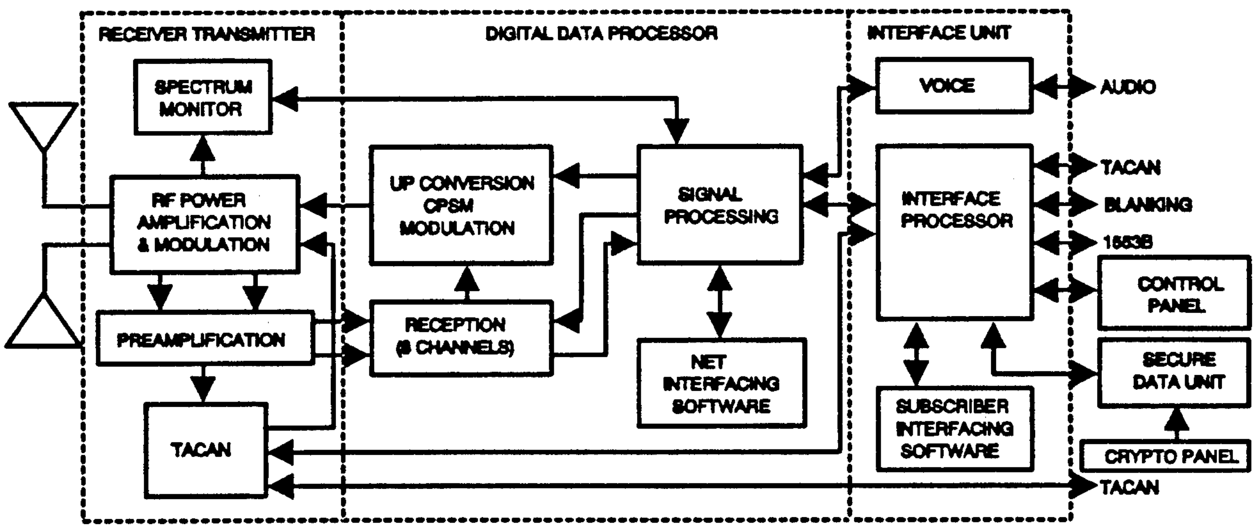

Figure III.6. Functional Partitioning of a Class 2 Terminal

The Communications Processor directs the functions of the terminal, controlling the terminal, processing the messages on reception and for transmission, processes input and output data from the interfaced elements, processes system time and models time drift. Communications Processing consists of the Interface Processor, Net Interfacing Software, Subscriber Interfacing Software and a Voice Encoder/Decoder. It interfaces with the operator via the Radio Set Control (Control Panel and Crypto Panel), the Secure Data Unit for encryption/decryption and various host vehicle interfaces.

III.3.2 Radio Set Control The Radio Set Control provides the operator interface for on-off control, Communications Processor initialization and Secure Data Unit variable loading.

III.3.3 Power Amplifier The Power Amplifier provides the final stages of RF amplification prior to transmission. The shipboard terminals may have additional power amplification for the capability of transmitting at multiple power levels, all but one of which are more than 200 watts. The airborne terminals transmit at only 200 watts. (These statements may be inaccurate.) Only the 200 watt transmission is of interest here. The high power outputs are for jammer burn-through and for overcoming cable loss. The shipboard power amplifier has an 800 watt capacity to account for 6 dB of cable loss.

III.3.4 Antenna Coupler Unit The Antenna Coupler Unit filters the transmit RF outputs, senses transmitted power levels and interfaces with either a single or dual antenna subsystem. For effective control of radiated power, the antenna coupler unit provides for four modes of connecting the transmitter to the antenna system. Specifically, the modes are:

1) Manual operation a) upper antenna only, b) lower antenna only or c) upper and lower antenna simultaneously

2) Automatic selection of upper or lower antenna.

In the reception mode, the antennas are selected to provide the most favorable signal to noise ratio. During signal acquisition (synchronization), 4 receiver channels can be connected to one antenna, while the 4 remaining receiver channels are connected to the other as an AJ measure in order that the antenna with the least jamming present can always be used to detect synchronization.

The Spectrum Monitor function safeguards against a terminal malfunction causing any electromagnetic interference in the IFF band. It also monitors the characteristics of the transmitted signal including pulse width, spurious emissions, and correct frequency hopping.

III.3.5 Secure Data Unit The Secure Data Unit provides encryption and decryption of messages under the control of the Signal Processing function. It is a KGV-8.[6] Figure III.7 presents the encryption/decryption process. Two types of security is involved: Transmission Security (TRANSEC) and Message Security (MSEC), both of which are a subset of Communications Security (COMSEC). TRANSEC applies to the Frequency Hopping sequence, the CPSM 32 chip sequence encryption, interleaving and jitter. MSEC applies to data message encryption. They use different cryptovariables. In fact, if the messages are from different sources, the may used different variables. The capability exists to store 8 operational variables. Cryptovariables are loaded with a KYK-13 or KOI-18, just as with GPS Receivers.

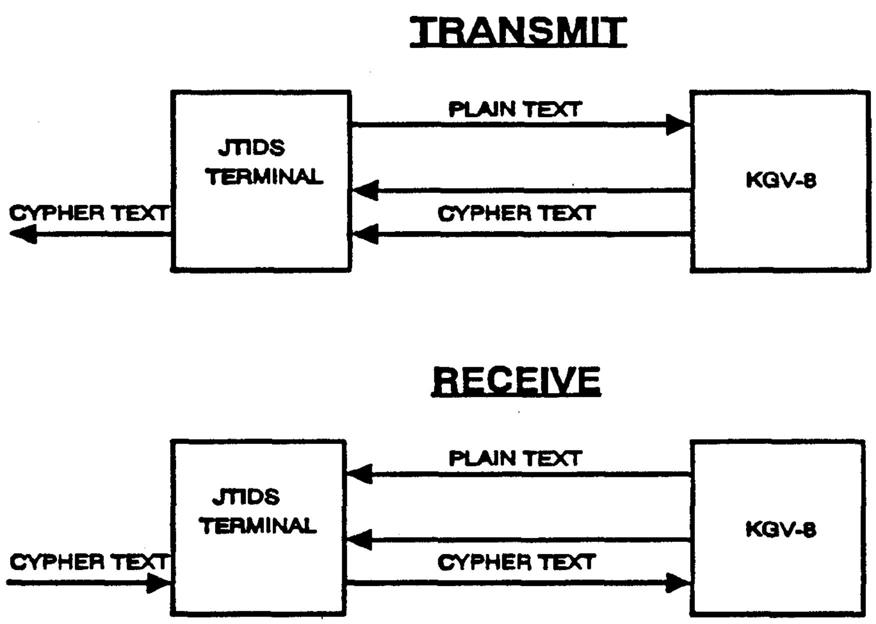

Figure III.7. KGV-8/JTIDS Terminal Interface

[6]Ira D. Ross, "JTIDS Communications Security", MITRE Institute Course Presentation, 21 October 1988.

The process is shown in Figure III.7 for both transmission and reception. In both cases, cypher text is provided by the KGV-8 for the TRANSEC functions. For transmission, plain message text is provided to the KGV-8 for encryption. Upon reception, encrypted cypher message text is provided to the KGV-8 for decryption.

Unfortunately, the KGV-8 is a device of moderate size, and is probably expensive. However, as indicated by Ross, there appears to be a development for the next generation KGV-8, which is called "Thorton VLSIC Application".

Chips are now available for embedded encryption within the Signal Processor.

III.3.6 TACAN The JTIDS terminals also include a TACAN function. However, that is not applicable to this study since this study is for a TACAN replacement.

III.4.0 JTIDS Performance

Without getting into a lot of detailed analysis, let it suffice to supplement the AJ margin analysis provided by Hughes Aircraft Company, and use those numbers to provide tradeoffs between AJ capability and LPI capability.

III.4.1 Signal-to-Noise Density There are two critical processes of interest with respect to the performance of a JTIDS terminal receiver. They are:

1) the process of signal acquisition and synchronization

2) the process of reading the message

Each of these processes have their own performance parameters, but both sets of parameters are related to a common parameter, which is signal-to-noise density, a parameter that is independent of the bandwidth of two processes. This signal-to-noise density is a function of the received signal power, the receiver's thermal noise density and received jamming signals. In the latter case, the case of jamming signals, the resulting noise density after the jamming signal is spread by the spread spectrum characteristics of the JTIDS signal, is dependent upon bandwidths of the signal, but, at a common point in the receiver, the effect on signal-to-noise density is common to both processes. This common point is that of a decorrelated symbol pulse (despread by the CCSK 32-bit code), which has an effective bandwidth of 156.25 kHz.

The resulting signal-to-noise density $\frac{S}{N_O}$, in ratio-Hz, including the effect of both thermal noise and jamming, is determined by

$$\left[\frac{S}{N_O}\right]^{-1} = \left[\frac{S}{N_{OT}}\right]^{-1} + \left[\frac{S}{N_{OJ}}\right]^{-1} \qquad \text{(III.6)}$$

where the signal-to-noise density, in dB-Hz, due to thermal noise is

$$\frac{S}{N_{OT}} = P_r - KT - L - NF \qquad \text{(III.7)}$$

where P_r is the received signal power given in Equation III.3, KT is the thermal noise density (-174 dBm/Hz), L is the total of signal losses, including antenna and cable loss and polarization and multipath loss, and NF is the receiver noise figure. In the E-3, the preamplifier is located at the antenna before the cable loss. In that case, cable loss mainly affects transmitter power loss, which is the reason for the high power amplifiers. On the E-3, the total noise figure, including cable loss, is less that 5 dB. Hughes Aircraft Company[7] indicated that on the F-14, L is up to 8 dB and NF to be 2 dB, for a total noise figure of approximately 10 dB. Thus, at 300 nm, Equation III.7 becomes

$$\frac{S}{N_{OT}} = -96 + 174 - 8 - 2 = 68 \text{ dB-Hz} \qquad \text{(III.8)}$$

The noise density, in dB/Hz due to the jammer is

$$N_{OJ} = \frac{J}{S} - PG_J - BW_P - L_J + P_r \qquad \text{(III.9)}$$

[7] Hughes Aircraft Company Proprietary Presentation titled "JTIDS Principles", dated 11 January 1988.

where $\frac{J}{S}$ is the jammer-to-signal power ratio at the input to the antenna, PG_J is the processing gain defined below, BW_P is the bandwidth of the pulse ($10 \log_{10} 156.25$ kHz = 51.94 dB-Hz) and L_J is the antenna and cable loss as it affects the jammer. The signal-to-noise density, in dB/Hz, due to the jammer is then

$$\frac{S}{N_{OJ}} = P_r - L - N_{OJ} \qquad \text{(III.10)}$$

Combining Equations III.9 and III.10 and inserting numerical values yields

$$\frac{S}{N_{OJ}} = PG_J - \frac{J}{S} + L_J - L + 51.94 \text{ dB-Hz} \qquad \text{(III.11)}$$

As discussed below, the processing gain is a function of type of jammer.

III.4.1.1 Processing Gain The processing gain of a JTIDS receiver, up through the CCSK demodulation of the received pulses, is illustrated in Figure III.8. Here, the processing gain is defined with respect to the receiver front end bandwidth. Since the frequency dehopping essentially filters out the unwanted frequency bands used by IFF, the front end bandwidth is the number of hops (51) times the bandwidth of each hop (3 MHz), for a total of 153 MHz, even though the preamplifier bandwidth is approximately 250 MHz. However, a jammer could have any bandwidth, so the processing gain for a given jammer would have to be computed based on the jammer's bandwidth, not the receiver's front end bandwidth. The exception to this is if a noise jammer is optimized for efficiency against the JTIDS receiver, in which case its noise spectrum would exactly match the JTIDS frequency band, and exclude the IFF bands.

A single frequency CW jammer is not very effective against the JTIDS signal because of the frequency hopping feature. This is because its power, on the average, only affects $\frac{1}{51}$ = 1.961% of the pulses, a factor that is easily accommodated by redundant frequencies and the Reed-Solomon error correction. In fact, during the synchronization period, it may not affect any of the pulses, since they occur on only eight of the 51 frequencies, and those 8 are randomly selected. With luck, the jammer would affect only $\frac{1}{8}$ of the pulses during synchronization. Also, the effect of a CW jammer on an affected pulse is even reduced further by the CCSK demodulation, since its energy is spread over the entire 3 MHz bandwidth of the pulse during the correlation process. Thus, for the purposes here, processing gain for a CW jammer won't be considered.

Because of the frequency hopping characteristics of the JTIDS signal, a reasonable jammer is forced to be of a noise type, unless it is a "smart" type that employs sophisticated techniques using its knowledge of the JTIDS waveform. "Smart" jammers won't be considered here. A noise jammer can, however, be smart enough to concentrate all of its energy in the known 153 Mhz frequency band used by JTIDS, instead of the entire 250+ MHz continuous frequency band. Whatever the band the noise jammer transmits in, the processing gain is simply the ratio of the bandwidth of the jammer to the bandwidth of a pulse, independent of the front end bandwidth of the JTIDS receiver. That is, for a noise jammer, the processing gain, in dB, is

$$PG_J = 10 \log_{10}\left[\frac{BW_J}{BW_P}\right] = 10 \log_{10} BW_J - 51.94 \text{ dB-Hz} \qquad \text{(III.12)}$$

where BW_J is the bandwidth of the noise jammer. Thus, for a selective 153 MHz noise jammer, the processing gain is 29.90 dB. For a 255 MHz noise jammer, the processing gain is 32.13 dB. Using the smaller of these two numbers, and using equal jammer and signal losses, Equation III.11 becomes

$$\frac{S}{N_{OJ}} = 81.84 \text{ dB-Hz} - \frac{J}{S} \qquad \text{(III.13)}$$

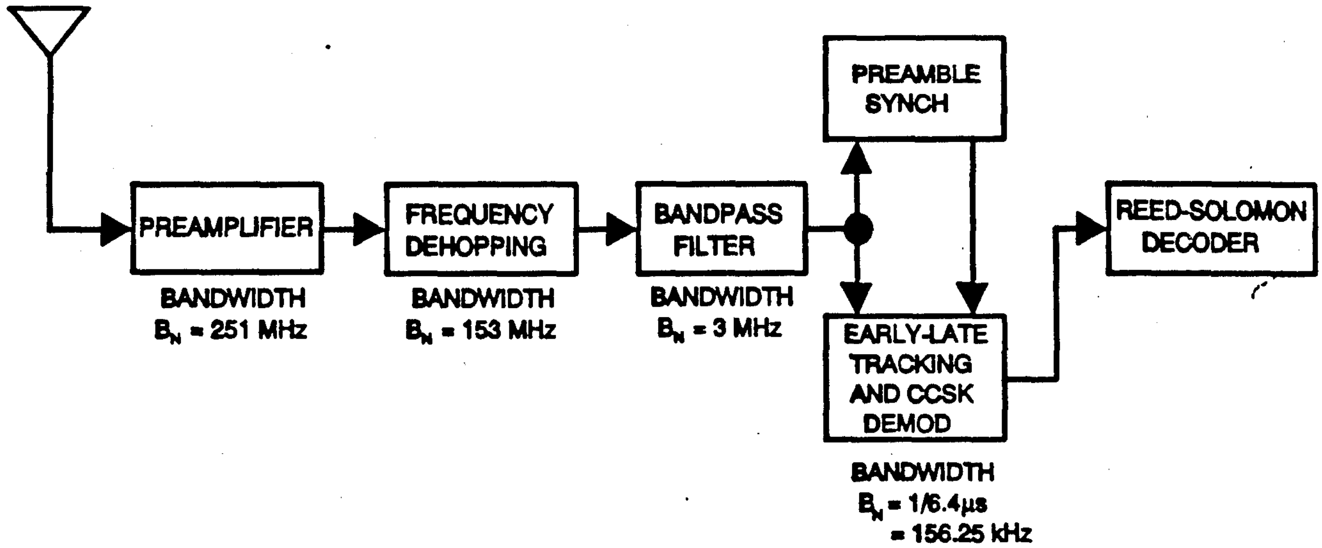

Figure III.8. Processing Gain Model of JTIDS Receiver

Note that a $\frac{J}{S}$ of 13.84 dB would result in a signal-to-noise density equal to that due to thermal noise. If the jammer were at a 300 nm distance, it would have to transmit 4.8 kilowatts of power to achieve that $\frac{J}{S}$. The actual AJ capability, however, is based on the required signal-to-noise density for synchronization and data recovery. This is the topic of the next section.

III.4.2 Required Signal-to-Noise Density and AJ Margin The required signal-to-noise density is different for synchronization than it for data recovery. Thus, each will be addressed separately.

III.4.2.1 Signal-to-Noise Density Required for Synchronization The energy (signal-to-noise ratio - SNR) required to synchronize to an incoming message (signal acquisition) is 15 dB. Now, this energy is accumulated over more than one pulse, so there is additional integration gain (IG) over the synchronization period, but with some implementation loss (IL). Thus, the total signal-to-noise ratio for synchronization is, in dB,

$$SNR_s = SNR_p + IG - IL \tag{III.14}$$

where the signal-to-noise ratio in the 156.25 kHz bandwidth, in dB, is

$$SNR_p = \frac{S}{N_o} - 51.94 \text{ dB-Hz} \tag{III.15}$$

Combining Equations III.14 and III.15, and solving for $\frac{S}{N_o}$ yields the required acquisition $\frac{S}{N_{oacq}}$ as

$$\frac{S}{N_{oacq}} = SNR_s - IG + IL + 51.94 \text{ dB-Hz} = 66.94 - IG + IL \text{ dB-Hz} \tag{III.16}$$

Hughes Aircraft Company indicated that the integration gain IG is 11 dB (non-coherent addition of 32 pulse correlation powers = $\log_2 32 \times 2.2$ dB), and that implementation loss IL is 2.5 dB, yielding a required $\frac{S}{N_{oacq}}$ of 58.44 dB-Hz, resulting in a 9.56 dB margin with respect that expected in the presence of thermal noise as given in

Equation III.8. Using Equation III.6 to then solve for $\frac{S}{N_{OJ}}$ yields a upper bound on $\frac{S}{N_{OJ}}$ of 58.95 dB-Hz, indicating that the jammer effect dominates at the threshold $\frac{S}{N_O}$. Using Equation III.13 and solving for $\frac{J}{S}$ yields a $\frac{J}{S}$ of 22.89 dB. Again, if the jammer were at a 300 nm distance, it would have to transmit 38.5 kilowatts of power to achieve that $\frac{J}{S}$ value. This $\frac{J}{S}$ value is sometimes called the AJ margin.

III.4.2.2 Verification of Analytical Results Using Probability of Detection Computations The computations described in Appendix II for computing the probability of detection were used to verify the results given above as well as the numbers provided in the Hughes Aircraft Company presentation. These results are shown in Figures III.9, III.10 and III.11. First of all, in Figure III.9, the probability of signal acquisition is given versus distance from the 200 watt transmitter. Three cases are shown. The first case is for the parameters indicated above, using the 8 dB cable loss and the computed 9.56 dB margin in the presence of thermal noise. This case verifies that margin at 300 nm. The other two cases neglect this margin to show the actual distance at which the signal could be acquired with no jamming present. One case shows the results for an improved system with only 1 dB of cable loss. With 8 dB cable loss, detection as high as 0.995 is possible at about 900 nm. With 1 dB cable loss, detection is possible at about 2050 nm. Of course, these distances are above the radio horizon. However, the additional margin can be used for more AJ margin or to reduce the transmitted power. Also, at higher $\frac{J}{S}$ values, the detection probability is lower, but still useful.

Figure III.10 provides the received signal-to-noise density that resulted in the probabilities presented in Figure III.9 for those same three cases. They are compared to the 58.44 dB-Hz $\frac{S}{N_{oacq}}$ value derived above. Note that the 300 nm range is verified at that value (within a dB) as are the range capabilities of the other two cases.

Finally, Figure III.11 presents the computed Decision Signal-to-Noise Ratio (SNR_D) defined in Appendix II for those three cases. All three cases indicate that about 18.5 dB for that quantity is required.

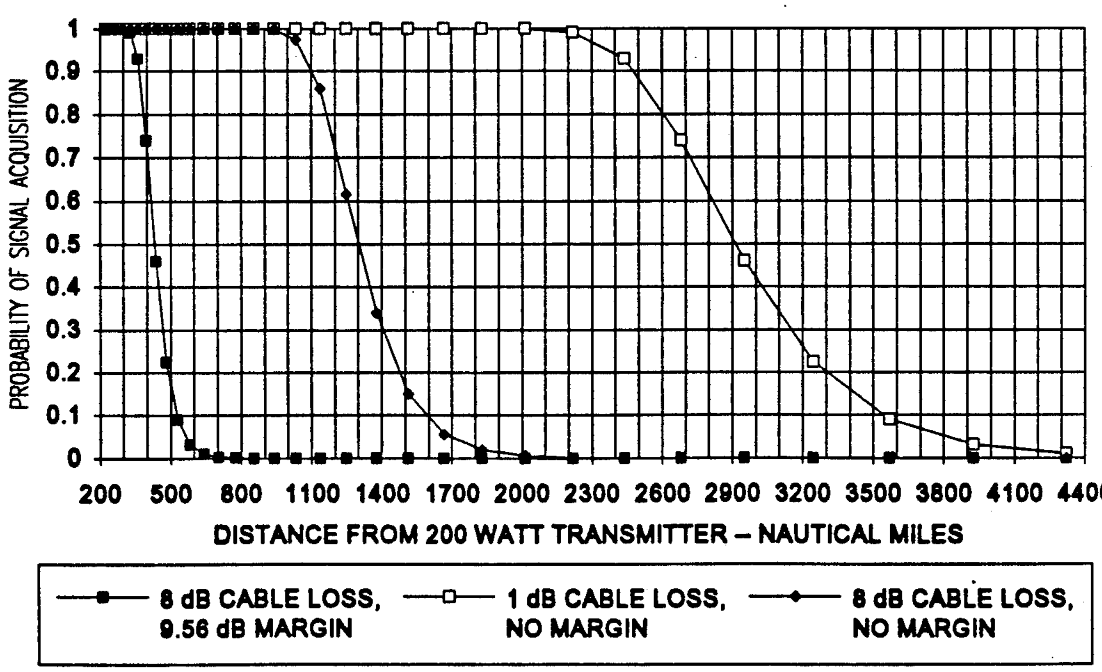

Figure III.9 JTIDS Probability of Acquisition

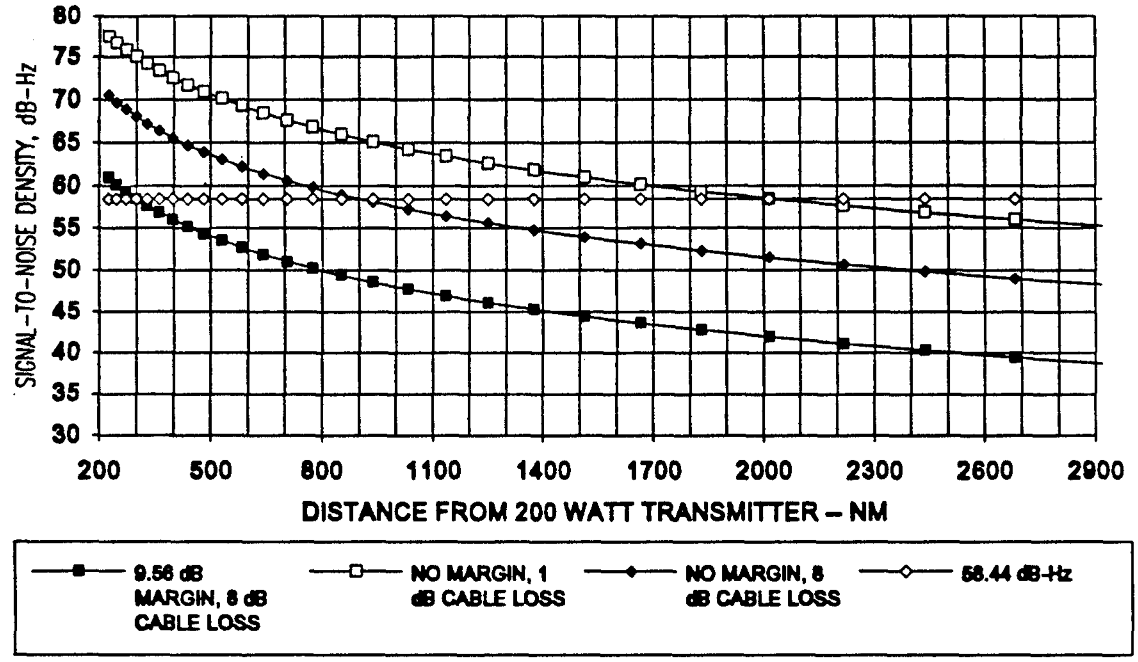

Figure III.10 Signal-to-Noise Density Required for JTIDS Signal Acquisition

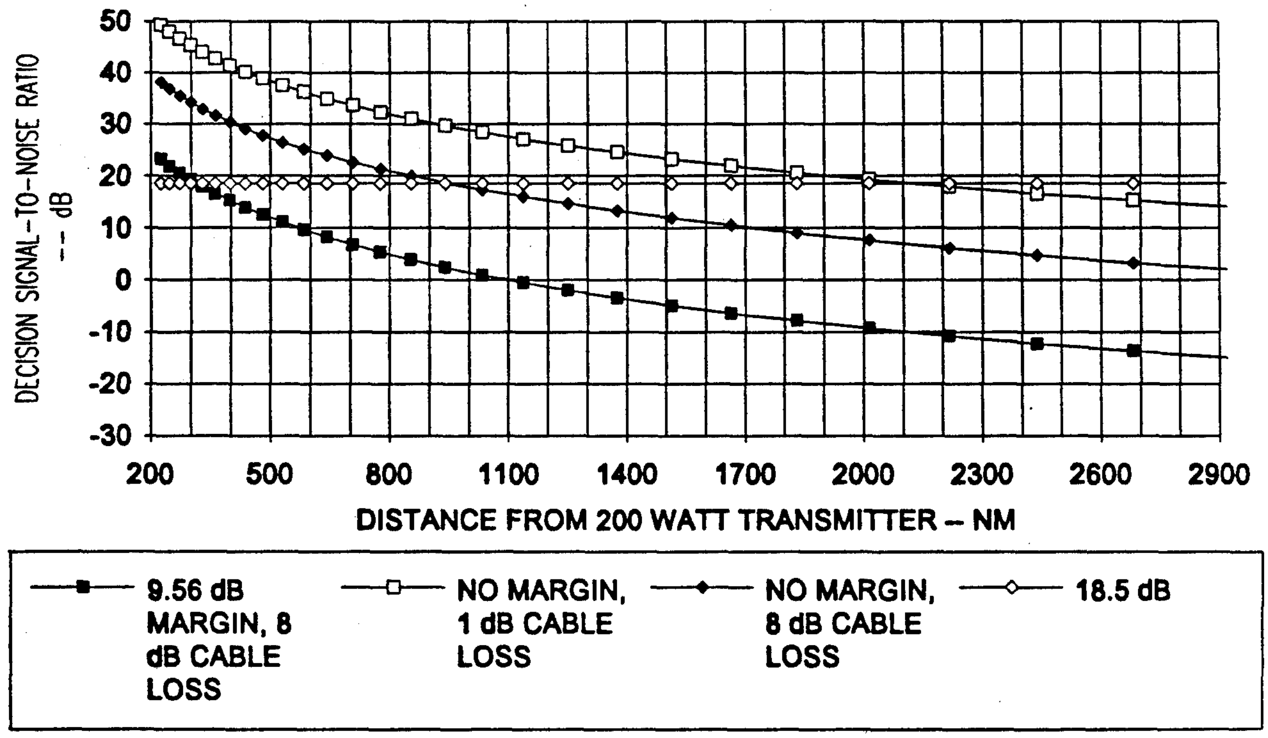

Figure III.11 Decision Signal-to-Noise Ratio Required for JTIDS Signal Acquisition

III.4.2.3 Signal-to-Noise Density Required for Data Recovery $\frac{S}{N_o}$ required for data recovery is a function of the bit energy $\frac{E_b}{N_o}$ in dB. The bit rate in a pulse is 781.25 kHz (5 bits in 6.4 μseconds). Thus, the energy per bit is, in dB,

$$\frac{E_b}{N_o} = \frac{S}{N_o} - 10\log_{10}(78125) + IG - IL = \frac{S}{N_o} + IG - IL - 58.93 \text{ dB-Hz} \qquad \text{(III.17)}$$

where IG is integration gain and IL is the 2.5 dB implementation loss indicated above. IG in this case is simply due to whether or not a double pulse message is used. If so, IG is 2.2 dB, the gain associated with the noncoherent addition of pulse correlation powers.

The data demodulation technique used on JTIDS amounts to correlating with the 32 orthogonal codes represented by the 5 bits per pulse. This is known as M-ary modulation and the demodulation as M-ary demodulation, which is a selection of one of M different orthogonal bit patterns. In this case M is $2^5 = 32$. The bit error rate P_b required for a decoded Reed-Solomon message error rate of 1% is 0.05. From Figure III.12, we see that requires an $\frac{E_b}{N_o}$ of 2.3 dB. Using Equation III.17 results in a required $\frac{S}{N_o}$ of 61.53 dB-Hz, providing a margin in thermal noise of 6.47 dB. As for the synchronization case, using Equations III.6 and III.13 yields an upper bound $\frac{J}{S}$ value or AJ margin of 19.15 dB, or a 16.45 kilowatt jammer at a distance of 300 nm.

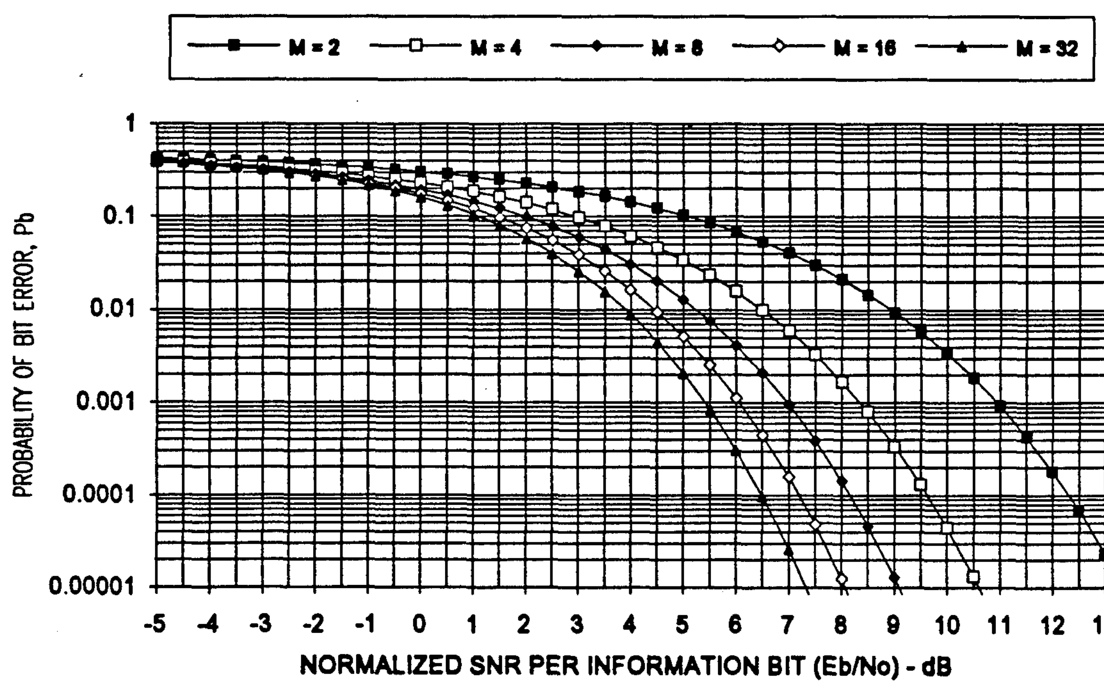

Figure III.12 Noncoherently Detected Orthogonal M-ary Signaling Performance

APPENDIX IV

DESCRIPTION OF 1553 BUS MESSAGES APPLICABLE TO THE REPLACEMENT OF SHIPBOARD TACAN WITH DGPS

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

IV.0 1553 Bus Interface Description

This appendix is a summary description of the information provided in ICD-GPS-059, related to the handling of inputs of waypoint and flight plan information and providing steering information, range to destination and time-to-go to destination and position and velocity information to the 1553 bus.

IV.1 Input Messages

IV.1.1 Destination Designation Input Message Input message I-3 is the Destination Designation Message. The Destination Designation Message is used to designate the waypoint to be used by the MAGR as the basis for steering information contained in output message G-3, Destination Data. It is assumed that it also designates the waypoint to be used by the MAGR as the basis for steering information supplied to the ARINC 429 interface to drive the flight instruments, although this was not specified in the ICD. The Destination Designation Message also designates the waypoint to be used to compose the output message G-4, Waypoint Data. The maximum input rate of this message is once per second.

The contents of the I-3 message include the following:

1) Destination Mode Word,

2) Waypoint Identification (ID),

3) Destination ID,

4) FROM Waypoint ID,

5) Entered Steering Course,

6) Entered Vertical Angle,

7) Magnetic Variation,

8) New Basic Waypoint Number,

9) Waypoint transferred to Basic Waypoint Number,

10) Flight Plan ID,

11) Flight Plan Start/Restart Waypoint ID,

12) direct-to Waypoint ID,

13) Holding Fix Waypoint ID,

14) Holding Leg Distance,

15) Holding Turn Radius,

16) Output Message G-25 Plan/Profile ID.

IV.1.1.1 Destination Mode Word The Destination Mode Word specifies the following options:

a) Steering course select The steering course selection is only used in the manual mode. It is not applicable to the use of moving waypoints, since rendezvous operations are used with moving waypoints, where the steering course is overridden with the selection of either the great circle route of the destination waypoint or the great circle route to the intercept point.

b) Vertical angle select The vertical angle (glide path angle) selection is only used in the manual mode. This selection is either that contained in this message, that stored with the selected waypoint or "no change" in vertical angle. During automatic sequencing of waypoints, this selection is not available.

c) Coordinate select The coordinate selection is either MGRS or latitude/longitude.

d) Waypoint auto sequencing This selection specifies whether manual destination waypoint selection is to be used (manual mode) or automatic waypoint sequencing using the predefined flight plan is to be used, whose ID is indicated in the message [See 10) above]. Setting this bit to a "1" starts the flight plan process and setting it to a "0" stops the flight plan process. Thus, for a sequence of waypoints defined in a flight plan, this message only has to be input twice -- once to start the flight plan, and one to stop the flight plan. In the manual mode, a new message is required for each new destination waypoint. In the automatic mode, a new waypoint is automatically selected from the flight plan each time the TO/FROM flag indicates "FROM". The Destination ID, FROM Waypoint ID, Entered Steering Course, Entered Vertical Angle and Magnetic Variation portions of the message are not process if the automatic sequencing is selected.

e) RNAV option select This allows the selection of 1) no RNAV, 2) Course Hold, 3) Holding Pattern and 4) direct-to options. In the Course Hold option, automatic sequencing is inhibited and the current course is followed until intersecting a line passing through the "TO" waypoint (selected prior to selecting Course Hold) that is perpendicular to the current course. At that time, the TO/FROM flag is switched to "FROM". This Course Hold option is disabled by activating the "direct-to" bit in a new message and specifying the next waypoint. If that waypoint is not in the active flight plan, automatic sequencing is terminated and so is the flight plan.

When a Holding Pattern Fix Waypoint is identified and the Holding Pattern option is selected prior to arriving at that waypoint, the RNAV computation is relative to that waypoint and automatic sequencing is suspended. It is not clear what the word "Fix" means. The new RNAV requirements specify that a holding pattern can be established at a moving waypoint. "Fix" here may mean position. This should be clarified.

When direct-to option is selected, Course Hold or Holding Pattern operation is cancelled. The direct-to waypoint ID must be specified in the same message. When arriving at this waypoint, automatic sequencing will be resumed provided that the direct-to waypoint ID specified is in the designated flight plan.

f) Chase/intercept select Chase/intercept selection is used during rendezvous operations to specify whether chase mode or intercept mode is desired. In the chase mode, the desired course is the same great circle path as that of the moving waypoint. In the intercept mode, the desired course is a great circle path from the present position to the intercept point (or point of closest approach).

g) Waypoint/intercept output select When the intercept mode is selected, this selection specifies whether current moving waypoint's position or the intercept position is to be output in the G-3 message.

h) Hold pattern position select This selection is used to specify whether the holding position is to the right or to the left of the course being flown just prior to entering the holding pattern.

i) Waypoint ID type The waypoint ID type is used to specify the format of the ID to be output in the G-4 message -- ICAO or Channel/Frequency.

IV.1.1.2 Waypoint Identification The waypoint ID, which is 6 ASCII characters designating the waypoint data to be output in the G-4 Waypoint Data message. These 6 ASCII characters are stored with the waypoint.

IV.1.1.3 Destination ID The Destination ID, which is 6 ASCII characters designating the destination waypoint to be used for computing the G-3 Destination Data message, but only if the destination ID is valid. If it is invalid, the G-3 message is computed for the last valid destination ID. An invalid ID is one that contains invalid characters or one that is not defined in the waypoint data base. In the manual mode, the Destination ID is utilized as the direct-to function.

IV.1.1.4 FROM Waypoint ID The FROM Waypoint ID, which is 6 ASCII characters designating the "FROM" waypoint in a "TO-TO" navigation mode implementation in the manual mode. It is not used in flight plan automatic sequencing mode.

IV.1.1.5 Entered Steering Course The Entered Steering Course, indicating a new true arrival desired course to be used for computing cross track deviation in the manual mode if this steering course is selected.

IV.1.1.6 Entered Vertical Angle The Entered Vertical Angle indicates a new vertical angle to be used for computing vertical deviation in the manual mode if this vertical angle is selected.

IV.1.1.7 Magnetic Variation The Magnetic Variation is that associated with the destination waypoint. A HEX value of FFFFH indicates that the magnetic variation is not included. This Magnetic Variation is not used by the MAGR.

IV.1.1.8 New Basic Waypoint Number The New Basic Waypoint or Waypoint Transferred to Basic Waypoint is used for transferring a waypoint in the MAGR's downloaded database to the basic waypoint file. Waypoints 1 - 24 are basic waypoints, 25 - 224 are waypoints in the MAGR's downloaded database. In the scheme of things for using moving waypoints for DGPS, the transferring of moving waypoints to the basic waypoint file does not apply. Moving waypoints can only be among the 24 basic waypoints. They are not allowed in the downloaded database. Thus, this word of the message as it applies to DGPS only specifies a New Basic Waypoint, specifying the use of a new waypoint to be used among the 24 basic waypoints. This may be one that had just been received via the data link via the I-4 Waypoint Definition Message, which has a waypoint number assigned to it. This capability exists. The ICD states that all Basic Waypoint data may be edited by the operator (in this case, the data link is the "remote" operator) using the I-4 message. For moving waypoints, the G-3 Destination Data output message position data is updated in real-time (within a second) to reflect the current position of the waypoint.

From a data link point of view, there is also a potential problem with waypoint numbers in general. The originator of the data link message has no idea what numbers are assigned to waypoints that already exist in the MAGR's Basic Waypoint data base. Thus, if the originator assigns numbers to uplinked waypoints, the MAGR may write over existing waypoints in the data base. However, the originator <u>does</u> know what numbers has been assigned to uplinked waypoints, so the originator certainly could designate one of those. The originator basically would be taking over this Basic Waypoint data base, unless some sort of protocol is used so the originator knows what numbers to assigned to uplinked moving waypoints. This protocol could be one where the originator can only assign certain numbers, while other numbers are reserved for other purposes or other originators. This potential conflict must be resolved.

IV.1.1.9 Flight Plan ID The Flight Plan ID is two ASCII Characters that has only two valid selections -- "PR" for primary and "AL" for alternate. The entered ID is automatically the "active" flight plan used as the basis for RNAV computations. If one is in operation when the other is selected, the switch between flight plans will occur automatically. Waypoint automatic sequencing must be selected to use the designated flight plan.

IV.1.1.10 Flight Plan Start/Restart Waypoint ID This ID specifies the specific waypoint in the flight plan that is to be used when other than the one designated as Sequence No. 1 is desired. Otherwise, and ASCII null is entered. This ID will only be used if entered prior to selecting automatic sequencing or to restart automatic sequencing if it had been inhibited for a course hold or holding pattern.

IV.1.1.11 Direct-To Waypoint ID This ID specifies the identifier of the designated terminal waypoint being used by the direct-to function. A flight plan will continue when arriving at this direct-to waypoint, as long as that waypoint is in the flight plan. If it isn't, the manual mode is entered. The direct-to function is only valid in the waypoint automatic sequencing mode.

IV.1.1.12 Holding Fix Waypoint ID This ID defines the waypoint at which the holding pattern is to be initiated. The holding fix waypoint must be part of a flight plan waypoint sequence. Thus, holding patterns cannot be implemented using the manual mode. If DGPS is used to direct the host vehicle to a holding pattern, DGPS must then use flight plans or modified flight plans. The desired altitude defined for the holding fix waypoint is the altitude that is used for RNAV vertical data computations.

IV.1.1.13 Holding Leg Distance This value defines the leg distance of the holding pattern. The MAGR doesn't do anything with this value except output it for external use when the Holding Pattern RNAV option is selected.

IV.1.1.14 Holding Turn Radius This value defines the turning radius of the holding pattern. As with the leg distance, the MAGR doesn't do anything with this value except output it for external use when the Holding Pattern RNAV option is selected.

IV.1.1.15 Output Message G-25 Plan/Profile ID This ID identifies the flight plan or flight profile to be output in the next G-25 Flight Plan/Flight Profile Data output message. During DGPS operations, the flight profiles do not apply.

This Destination Designation message is the means by which an air traffic controller can designate previously uplinked moving waypoints for controlling the flight path of the aircraft. Positive response of his designation can then be a downlink of the corresponding G-4 Waypoint Data and G-25 Flight Plan/Flight Profile Data output messages, which indicate which waypoints and/or flight plan is being used by the MAGR.

There are 480 bits of data in the I-3 Destination Designation input message. However, at least 96 of these bits are associated with the manual mode. It will appear that in the following discussions that DGPS be best implemented using dynamic flight plans with the automatic sequencing mode. If the manual mode is not used in the implementation of DGPS, the data link need not transmit them, provided the mission computer defines them when building messages for the MAGR.

IV.1.2 Waypoint Definition Input Message Input message I-4 is the Waypoint Definition Message that contains the parameters that define either stationary or moving waypoints. The Waypoint Definition Message can be input during the MAGR's INIT and NAV modes. For DGPS operations, input during the NAV mode only applies. Also, if holding patterns are to be implemented using DGPS, these input waypoints are either those to be used in a flight plan. In this case, an I-25 Flight Plan Definition Message must also be sent to delete old or invalid waypoints and to add the new waypoint(s) to the flight plan. Changes in the I-4 message are reflected in the G-4 Waypoint Data output message within one second of receipt of the I-4 message, but only if the waypoint ID in the I-3 message is the same as the waypoint ID in the I-4 message. (This is assumed to mean any previously received I-4 message.) The maximum rate at which the MAGR will accept the I-4 message is once per second.

The contents of the I-4 message include the following:

1) Waypoint Mode Word,

2) Waypoint Number,

3) Waypoint ID,

4) Waypoint Position,

5) Desired Altitude,

6) Datum Number,

7) Magnetic Variation,

8) Desired Vertical Angle,

9) Desired Course,

10) Offset Range,

11) Offset Bearing,

12) Ground Speed,

13) Ground Track,

14) Starting Time,

15) Reference Waypoint ID,

16) Slaved Variation,

17) Initiating Altitude.

IV.1.2.1 Waypoint Mode Word The Waypoint Mode Word indicates which contents of the message to use via validity indicators and which magnetic variation to use (that which is computed by the MAGR or that sent in the message). The contents of the message for which validity is indicated are course specified, vertical angle specified, moving waypoint specified, slaved variation, whether or not position is valid for the G-4 output message, and whether or not a reference waypoint is specified. It also specifies whether or not the desired altitude or the initiating altitude in the message should be used.

IV.1.2.2 Waypoint Number This input message only applies to the input of Basic Waypoints, which includes the moving waypoints. Thus, the waypoint number range is 1 to 24. A protocol has to be set up to assign these number. This protocol will probably be with the Mission Computer that has access to the numbers stored with in the MAGR via the G-4 output message.

IV.1.2.3 Waypoint ID The Waypoint ID in this message has the same form as that in the I-4 Destination Designation input message. This ID is that of the waypoint being defined.

IV.1.2.4 Waypoint Position The waypoint position is a horizontal two-dimensional position defined either in MGRS coordinates or in Latitude/Longitude. If it is the latter, the first two words are made up of ASCII @'s. The coordinate frame for the latter is defined by the datum number.

IV.1.2.5 Desired Altitude Desired Altitude is the altitude above mean sea level of the defined waypoint (whether the offset function is used or not). When defining a glidepath, this is the altitude of the reference waypoint.

IV.1.2.6 Datum Number This is a number between 1 and 47 specifying the map datum number of the waypoint's coordinates. These datums are stored in the MAGR.

IV.1.2.7 Magnetic Variation This is the difference between true north and magnetic north at the waypoint. If is specified as a Hex FFFF, the MAGR will use its own algorithm to compute magnetic variation.

IV.1.2.8 Desired Vertical Angle This is the arrival desired vertical angle at the waypoint.

IV.1.2.9 Desired Course This is the desired course at the waypoint. Since the MAGR computes the desired course for moving waypoints, this value does not apply. However, DGPS can be used for fixed waypoints as well, in which case it can apply.

IV.1.2.10 Offset Range/Offset Bearing Offset range and offset bearing define an offset waypoint in terms of a slant range and true bearing from the position of the reference waypoint. If the reference waypoint ID has not been specified, these offsets are with respect to the waypoint position defined in the message. From this position, range and bearing, the position of the new waypoint is computed. The waypoint ID and waypoint number refer to this new waypoint, not the reference waypoint. When the reference waypoint ID is supplied, the position supplied in the message is Hex FFFFs, and the MAGR uses a previously supplied waypoint from the data base with the reference ID.

IV.1.2.11 Ground Speed/Ground Track Ground speed and ground track make up the velocity vector of a moving waypoint at the starting time. The track is reference to true north.

IV.1.2.12 Starting Time This is the time that a moving waypoint will start moving from the defined position along the specified velocity vector. The position output in the G-4 message requested in the I-3 message is that defined position. The position output in the G-3 message for the destination ID selected will be the newly computed waypoint position propagated using the velocity vector.

IV.1.2.13 Reference Waypoint ID This ID identifies the reference waypoint for using offset range and bearing to define a waypoint.

IV.1.2.14 Slaved Variation Slaved variation is the value of the distance between true north and the 000 radial of the TACAN or VOR station associated with the waypoint. Of course, since the purpose here is to replace Shipboard TACAN with DGPS, this value does not apply.

IV.1.2.15 Initiating Altitude Initiating altitude is the altitude above mean sea level of the new waypoint and is used to define one end point of the glide path. Desired altitude is the other end point (destination).

Since, in the general case, holding patterns can not be specified in the manual waypoint sequence mode, it will be necessary to use updated flight plans using DGPS. For flight plans, this message is used to update the waypoints sequenced in the flight plan.

The I-4 Waypoint Definition Message contains 480 bits of data. As with the Destination Message, some of the words do not apply to the application of DGPS, and thus the data can be compressed somewhat for transmission. However, if it is, the mission computer will have to create words to add to the message for communication with the MAGR.

IV.1.3 Flight Plan Definition Input Message The I-25 Flight Plan Definition input message contains the entries to define or modify a given flight plan. A maximum of 2 unique flight plans, each containing a maximum of 30 waypoints, can be stored in the MAGR data base. Since, for DGPS using moving waypoints, the waypoints must be stored as Basic Waypoints, this maximum is really 24. This message is processed at a maximum rate of 5 Hz.

The contents of the I-25 message include the following:

1) Mode Word

2) Plan ID

3) Sequence Number

4) Designation ID

IV.1.3.1 Mode Word The mode word provides one of four meanings: no update, add a waypoint, delete a waypoint or add a profile. The no update mode doesn't appear to be required, since the only use of this message is to update the flight plan. For DGPS, adding a profile does not apply, since profiles cannot contain moving waypoints. Adding a waypoint applies to both defining a flight plan or modifying an existing flight plan. Deleting a waypoint only applies to modifying an existing flight plan. The procedures for both are provided below.

IV.1.3.2 Plan ID The plan ID identifies the flight plan being defined or modified. It must be one of two values: PR (for primary) or AL (for alternate). The MAGR only computes RNAV data for one plan at a time. They can be switched at any time via the I-3 Destination Designation input message. If a switch occurs, the newly selected flight plan becomes effective within 4 seconds. Flight plans are also initiated, inhibited and terminated via the I-3 message. Each flight plan consists of up to 30 waypoints, although, as stated above, only 24 can be used for DGPS using moving waypoints. Also, for DGPS using moving waypoints, these waypoints can only be defined individually with the I-4 Waypoint Definition input message, which must be defined before the flight plan can be defined or modified.

IV.1.3.3 Sequence Number For a newly defined flight plan, this number, ranging from 1 to 30, indicates the position of the waypoint in the flight plan. A "1" indicates the first waypoint in the flight plan. A review of the flight plan can be accomplished via the G-25 Flight Plan/Flight Profile Data output message upon request using the I-3 input message.

For flight plan updates, when a waypoint is added, the sequence number indicates where the waypoint is to be inserted in the flight plan. The MAGR then increments the sequence number of all previously entered waypoints of that sequence number and higher by one. If the update is form of a deletion, the MAGR decrements those sequence numbers by one to fill the vacated position. Insertion will fail if it results in more that 30 sequence numbers. To change a waypoint stored in the flight plan, it is best to first delete the waypoint of that sequence number, or an obsolete waypoint, and then insert the new one.

IV.1.3.4 Designation ID The designation ID is the ID of the waypoint to be added or deleted from the flight plan.

It is required that desired altitude be specified in the I-4 messages used to define the waypoints of the flight plan to be used in the computation of flight plan related RNAV data.

If a current flight plan is being modified during the current leg, that modification is accomplished by first commanding a "course hold" function in the I-3 message, then entering the flight plan changes required, then commanding the "direct-to" function using the I-3 again to the new waypoint in the flight plan to resume auto-sequencing.

The I-25 Flight Plan Definition Message contains 112 bits of data, all of which are required for DGPS operations. The message is required only when a flight plan changes. Note that future waypoints can be changed before being activated via the sequence, effectively changing the flight plan without this message. This message is only required if the ID of a current or future waypoint changes. However, if a current destination waypoint changes, whether or not its ID changes, the "course hold" and "direct-to" functions must be initiated.

IV.1.4 Input Messages Summary Three input messages via the 1553 bus are applicable to the Shipboard TACAN Replacement using DGPS. They are:

1) I-3 Destination Designation Input Message

2) I-4 Waypoint Definition Input Message

3) I-25 Flight Plan Definition Input Message

It appears that the use of flight plans is desirable for the implementation of DGPS because of the automatic sequencing feature for two reasons. The first is that holding patterns are not available in the manual mode. The second is that programmed flight plans such as curved approaches, etc. can be accomplished using the automatic sequencing capability of a flight plan without continuous updates via an I-3 message. That is, a string of I-4 messages defining waypoints along a flight path can be sent, followed by a string of I-25 messages defining the sequence of how those waypoints should be used. Furthermore, those waypoints can be moving waypoints defined with respect to a moving ship.

For some cases, the messages as defined may be awkward to use and somewhat inefficient. However, they appear to be sufficient to implement DGPS. Some of that inefficiency can be eliminated by defining data link messages that do not include all the entries of these three messages, because some of those entries would never be used in the DGPS implementation. This would require that a protocol be established in the host vehicle's mission (or flight control) computer. But that is probably required anyway. For example, that computer will probably have to manage the MAGR's Basic Waypoint data base to ensure that waypoints are to be used in the future are not overwritten with new ones.

To verify the receipt of these messages and verify the correct DGPS and RNAV implementation of the transmitted messages, it will be necessary for the MAGR and the mission computer to output return messages. Furthermore, the MAGR must output messages requested by the mission computer for flight instrument and CDU displays. The applicable MAGR output messages are described in the following discussions.

IV.2 Output Messages

IV.2.1 Destination Data Output Message The G-3 Destination Data output message contains area navigation information regarding the manual destination or flight plan specified in the I-3 Destination Designation input message. The MAGR updates this message at a rate of 5 Hz in the NAV mode only. Changes in the I-3 message are reflected in this G-3 output message within one second of the receipt of the I-3 message.

The contents of the G-3 output message are essentially a repeat of the relevant contents of the I-3 input message plus current steering, range and time-to-go to destination information. This information could be used by an aircraft's mission computer or CDU to provide guidance information to the pilot or navigator in those aircraft installations where the MAGR doesn't drive the displays. Specifically, the contents of the G-3 output message are as follows:

1) Destination Mode Word,

2) Destination Waypoint Number,

3) Destination ID,

4) Bearing to Destination,

5) Computed Magnetic Variation,

6) Slant Range to Destination,

7) Time to Destination,

8) Steering Course,

9) Selected Vertical Angle,

10) Cross Track Error,

11) Vertical Angle Error,

12) Ground Speed,

13) Ground Track,

14) Starting Time,

15) Latitude,

16) Longitude,

17) Miss Distance,

18) Flight Plan ID,

19) Along Track Distance,

20) Holding Leg Distance,

21) Holding Turn Radius.

IV.2.1.1 Destination Mode Word The Destination Mode Word specifies the following:

a) Steering course select Steering course select indicates which steering course option was used to compute the cross-track deviation. When flight plan (automatic sequencing) is used, it will indicate "Default Course Used". If moving waypoints are used, the selection will be either the great circle route of the destination waypoint or the great circle route to the intercept point, depending upon which was rendezvous mode was selected.

b) Vertical angle select The vertical angle (glide path angle) indicates which vertical angle was used in computing vertical error. When flight plan automatic sequencing is used, the vertical angle is indicated as not defined.

c) Waypoint auto sequencing Waypoint automatic sequencing is used if a flight plan was selected for RNAV computations. Otherwise the manual mode is used for RNAV computations.

d) Rendezvous mode Rendezvous operation is indicated when moving waypoints are being used. Otherwise, normal RNAV operation is indicated.

e) Chase/intercept select This selection is only valid in the rendezvous mode. It indicates whether the chase mode or the intercept mode is being used for RNAV computations. In the chase mode, the desired course is that of the great circle route of the moving waypoint. In the intercept point, the desired course is that of the great circle path between the host vehicle and the intercept point.

f) Intercept possible Intercept possible is indicated only during the rendezvous/intercept mode. If the intercept is not possible, the point of closest approach and the miss distance is computed. In a rendezvous with a ship, intercept should always be possible.

g) Waypoint/intercept In the intercept mode, it is indicated whether the current moving waypoint's position or the intercept's position (or point of closest approach) in this message.

h) Destination error The waypoint is not valid. This is an error condition.

i) Hold pattern position select A hold pattern is indicated when the hold pattern is enabled.

IV.2.1.2 Destination Waypoint Number This the number assigned to the waypoint that is currently the destination to which the RNAV data is being computed. This number seems to be redundant with the Destination ID.

IV.2.1.3 Destination ID The destination ID is the identification of the destination waypoint used for computing the data output in this message.

IV.2.1.4 Bearing to Destination This is the true bearing from the present position computed by the MAGR to the destination waypoint. For moving waypoints, it is the true bearing to the instantaneous waypoint location, not the intercept point.

IV.2.1.5 Slant Range to Destination This is the slant range from the present position computed by the MAGR to the current destination waypoint, whether it is stationary or moving. However, in the intercept mode, it is the slant range to the intercept point (or point of closest approach).

IV.2.1.6 Time to Destination Time to destination is the estimated time to the destination (or intercept point) if the current velocity is maintained along the great circle route.

IV.2.1.7 Steering Course Steering course is the true north reference course used for computing cross track deviation. In the intercept mode, it is the desired course to the intercept point or the point of closest approach.

IV.2.1.8 Selected Vertical Angle The vertical angle is that being used to compute vertical error. However, in the flight plan automatic sequencing mode, it is not used. Then, vertical navigation is computed using the desired altitude stored with the waypoint.

IV.2.1.9 Cross Track Error The cross track error is the perpendicular distance from the desired track (course).

IV.2.1.10 Vertical Angle Error Vertical angle error is the angular deviation from the current glide path to the desired glide path.

IV.2.1.11 Ground Speed/Ground Track/Starting Time These are the values stored with the current moving waypoint being used for RNAV computations.

IV.2.1.12 Along Track Distance This is the distance along the desired course to the destination waypoint (moving or stationary) from the perpendicular line from the desired course to the host vehicle. In the intercept mode, this distance is to the intercept point.

IV.2.1.13 Waypoint/Intercept (Latitude/Longitude) Position When not in the intercept mode, these are the position of the current destination waypoint's position (moving or stationary). When in the intercept mode, they are the position of either the moving waypoint or the intercept position, depending on the chosen option in the I-3 input message. If the intercept is not possible, they are the position of the point of closest approach.

IV.2.1.14 Miss Distance If an intercept is not possible, this is the projected miss distance from the intercept point.

IV.2.1.15 Flight Plan ID This is the identification of the current flight plan being used, either PR or AL.

IV.2.1.16 Computed Magnetic Variation This is the magnetic variation currently being computed by the MAGR at the present position.

IV.2.1.17 Holding Leg Distance If the holding pattern is enabled, this is holding pattern leg distance that is stored with the holding pattern waypoint.

IV.2.1.18 Holding Turn Radius If the holding pattern is enabled, this is the holding pattern radius stored with the holding pattern waypoint.

Most of this data is of use only to the mission computer for flight instrument and CDU display, thus satisfying and exceeding the display requirements for the replacement for Shipboard TACAN. However, some of it may be useful to and air traffic controller and could be transmitted via the data link.

IV.2.2 Waypoint Data Output Message The G-4 Waypoint Data output message contains the waypoint output data associated with the waypoint designated in the I-3 Destination Designation input message. The MAGR updates this output message at a 1 Hz rate in the INIT and NAV modes. Changes in the I-4 Waypoint Definition input message are reflected in this G-4 output message within 1 second of receipt of the I-4 message if the valid waypoint ID in the I-3 message is the same as the waypoint ID in the I-4 message.

The contents of the G-4 output message are identical to the I-4 input message. These contents can be used as verification of the correct reception to the I-3 and I-4 messages via a data link, which will be useful as a feedback mechanism in an air traffic control environment. Other than that, this message is of no use to the replacement of Shipboard TACAN.

IV.2.3 Flight Plan/Profile Data Output Message The G-25 Flight Plan/Profile Data output message contains the parameters that are defined in the Flight Plan input message (I-25). It also can be used to output the flight profiles. However, flight profiles only consist of non-editable stationary waypoints and do not apply to the replacement of Shipboard TACAN. If the mission computer specifies a valid flight plan in the I-3 Destination Designation input message, the MAGR will output, when requested, flight plan data in the G-25 message. The message contains 6 waypoint IDs. The flight plan will be output starting with the sequence number 1 waypoint ID and continue in 6 waypoint blocks at a 5 Hz rate. The content of the message is a mode word, indicating whether it is outputing a flight plan or a profile, the flight plan/flight profile ID, and six sets of the following:

1) Sequence number,

2) Waypoint ID,

3) Desired Altitude.

The message is useful for verification purposes only. Its contents could be transmitted for air traffic control verification.

IV.2.4 RNAV Status Output Message The G-26 RNAV Status output message is updated at a 1 Hz rate. It consists of RNAV status, detected RNAV errors, a Basic Waypoint, holding pattern information and the FROM waypoint ID.

The RNAV status verifies what RNAV modes that are currently being processed in the MAGR. The detected RNAV errors are those that are probably due to invalid entries via the 1553 bus. The Basic Waypoint list is by waypoint number and lists those that are not present or have been entered. These status, errors and waypoint list will be useful for protocol information between the MAGR and the mission computer. The waypoint list is especially helpful for keeping track of what Basic Waypoint numbers are in use for managing the Basic Waypoint memory in the MAGR.

Although the holding fix is used by the MAGR, the other holding pattern information in this message is not. Either the mission computer or the pilot will use this information to navigate in the holding pattern.

The FROM waypoint ID is of no use to DGPS because it is applicable to only the manual mode of RNAV.

IV.2.5 Other Useful 1553 Bus Output Messages None of the output messages described above have any information about the location of the host vehicle, except for the computed slant range and bearing to a waypoint. In an air traffic control environment, the report of the host vehicles position and velocity would be useful in tracking the host vehicle without the use of surveillance radar. Thus, an output message containing that information is useful. There are a number of such messages output to the 1553 bus. They are:

1) G-6 GPS Foreground Navigation Output Message,

2) G-8 Background Navigation Data Output Message 1 (ECEF),

3) G-9 Background Navigation Data Output Message 2 (Lat/Long),

4) G-15 Time Mark Pulse Output Message 1,

5) G-17 Data Capture Pulse Output Message 1,

6) G-28 F-15 GPS State Vector.

The G-6 GPS Foreground Navigation output message contains the right information for position reporting, but puts it out at a much higher rate than is required for position reporting. Unless it is being output to the mission computer for other purposes, it is not recommended for the purpose of position reporting.

The G-8 and G-9 Background Navigation Data output messages both put out the same information, except that the former puts it out in the Earth-Centered-Earth-Fixed (ECEF) coordinate frame. Position reporting should be in terms of latitude and longitude. Thus, the G-9 message is more appropriate. This output is at a 1 Hz rate, which is more than adequate for position reporting.

The G-15 Time Mark Pulse and G-17 Data Capture Pulse output messages are meant for applications where the time-tagging of the output is critical. Both outputs are in the form of ECEF coordinates. Thus, these outputs are not appropriate for position reporting.

The G-28 F-15 GPS State Vector output message replaces the G-6 GPS Foreground Navigation output message on the F-15. It expresses position in terms of quaternions. This also is not appropriate for position reporting.

It appears that the G-9 Background Navigation Data output message is the most appropriate for obtaining position and velocity of the host vehicle for position reporting.

APPENDIX V

DERIVATION OF PSEUDOLITE SIGNAL STRUCTURE

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

V.0 Derivation of Pseudolite Signal Structure

A pseudolite (PL) is a one-way data link in the form of a shipboard transmitter that transmits a GPS-like signal with a signal structure that is compatible with the GPS satellite signals at one or both of the GPS frequencies. These signals can also serve as ranging signals. In this appendix, the application of Shipboard TACAN Replacement requirements to pseudolites are addressed to point out the advantages and disadvantages of such an application, and a PL signal structure is derived.[1]

The obvious largest advantage that the use of PLs as the DGPS data link provides is the fact that no data link external to the airborne GPS receiver is required, as that receiver itself can be used as the data link receiver. There are other advantages, but they are secondary to that one. The most obvious disadvantage is the possibility that PLs could interfere with the reception of GPS satellite signals. For this reason the most important factor to consider with respect to the use of PLs as a DGPS data link is that of reception reliability, especially their EMI effects on the reception of the GPS satellite signals. Because of this, it is imperative that the PL signal structure be derived in a way to minimize these EMI effects, and then consider the other factors based on that derivation. The following discussions emphasize this.

V.1 The Near-Far Problem There are two reasons for the potential interference effects of a PL on the reception of the GPS satellite signals. One is because the distance between the PL and the airborne and shipboard receivers is small compared to the distance between them and the satellites. A more important reason is because the distance between the airborne receiver and the PL can vary significantly. If the PL's power output is set for adequate reception at a given distance, it will be strong at smaller distances, and could interfere with the satellite signals and could even possibly saturate the GPS receiver's circuitry. However, by using a pulse modulated signal, this problem can be solved. That solution also allows the shipboard GPS receiver itself to track the satellites at the same time the PL is transmitting. This pulse modulation solution will be analyzed in detail below.

V.2 Pseudolite Design Overview A PL in this application is a ship-based transmitter that is synchronized to GPS time and has a signal structure that may be different, but compatible with the GPS satellites. For the purpose of the discussions here, the PL has two functions -- to transmit DGPS information to the participating airborne GPS receivers in the local area, and to possibly provide signal augmentation for the airborne receivers for ranging or integrity purposes.

There are two reasons for synchronizing the PLs transmitted signal to GPS time -- one to aid acquisition of its signal by the airborne receiver, and the other to provide that receiver with a ranging signal with respect to the ship. The accuracy of synchronization required to aid acquisition is not as demanding as that required to provide a ranging signal. Thus, the method of synchronization is highly dependent upon whether or not the ranging signal is required.

The purpose of providing a ranging signal is twofold. First, it can be used as an integrity check against the range computations made by the airborne receiver. The measured range should be close to that computed. Second, range rate derived from the carrier tracking of the PL signal can provide an accurate rate-of-closure to the ship. Whether either of these capabilities are required will impact shipboard integration requirements.

The method of synchronizing a PL to the GPS satellites can be achieved by collocating it with a DGPS Reference Receiver (RR) as illustrated in Figure V.1. In this collocated configuration, the RR shares the transmit/receive antenna with the PL, which also allows for self-calibration. This is the concept implemented in the DoD's Range Applications Joint Program Office's Ground Transmitters.[2] This concept may be required if precise ranging from the PL is desired.

---

[1]This subject was addressed in the paper "Concepts for Replacing Shipboard TACAN with Differential GPS" by A. J. Van Dierendonck, Proceedings of ION GPS-90, the ION Satellite Division 3rd International Technical Meeting, Colorado Springs, CO, 17-21 September 1990. However, this report addresses this subject in more detail and consists of changes based on information not known when that paper was written.

[2]System Specification for Global Positioning System (GPS) Ground Transmitter (GT) - Type A, SS-GT-100, 23 December 1988.

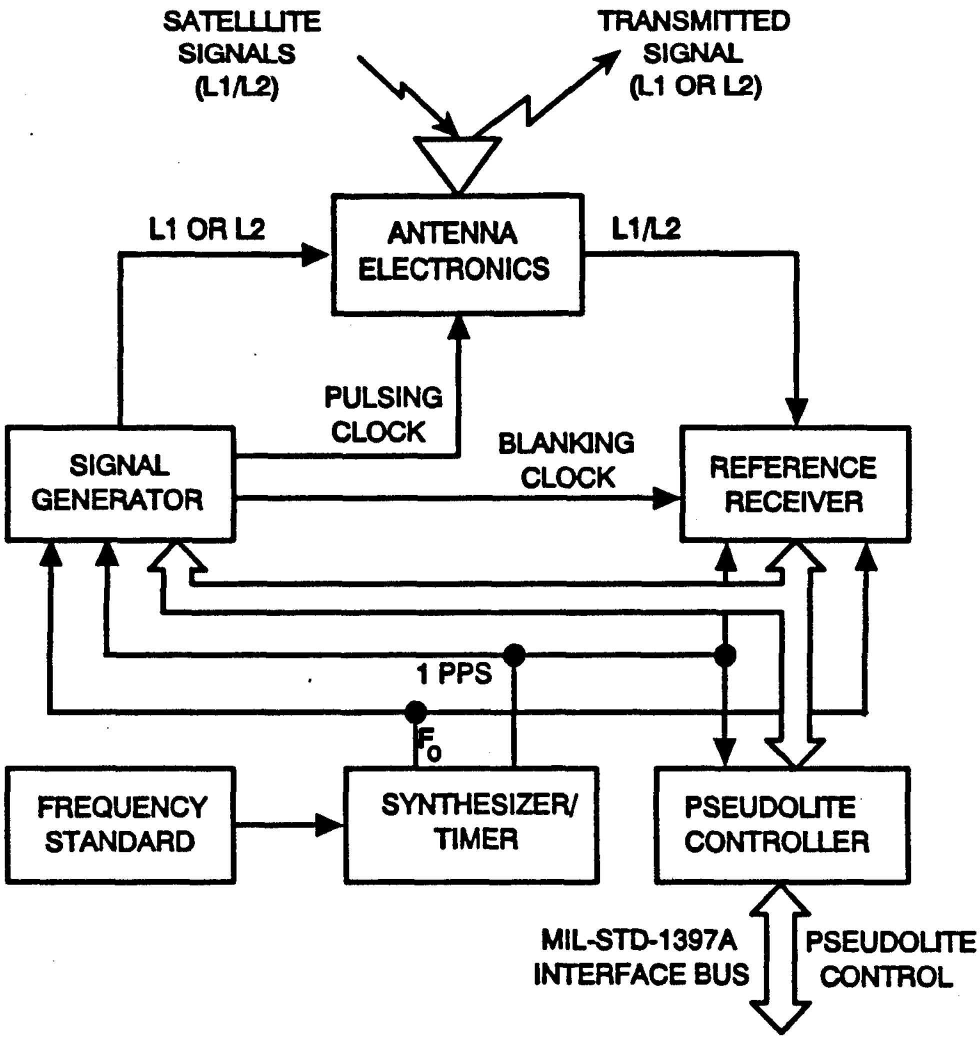

Figure V.1. Collocated PL/RR Concept

Another less accurate method of synchronizing a PL to the GPS satellites can be achieved by simply synchronizing it to a synchronization pulse from the shipboard GPS RCVR-3S, in which case the PL would be free running with periodic time updates from the shipboard receiver. This concept is illustrated in Figure V.2.

In the collocated PL/RR approach, both the RR and the PL signal generator derive their timing coherently from the same frequency standard. The signal generator generates the PL signal by superimposing the PN code and DGPS data on the generated carrier. It also generates the clocking for the pulses for the transmission of the PL signal, in order to minimize interference to GPS receivers in the local area. This pulsing also allows the RR to receive the GPS satellite signals via the same antenna by blanking its input signal during the pulse period. In fact, by providing a suitable calibration path the RR can also track the output of the signal generator when the pulses are not present, because the signal can be generated continuously. Only the transmitter power amplifier is pulsed on and off. In this way, the collocated PL is self-calibrating, and the transmitted PL signal will be synchronized to the same clock that is used to derive the ship's position and velocity and GPS time. Furthermore, signal integrity is partially monitored by the RR. There is no way that the RR can monitor the pulses. However, because of their magnitude, there are other means of monitoring their existence as well as their energy.

The above description is for a PL with a dedicated GPS receiver. In as much as the ships will already be outfitted with the DoD's shipboard GPS receiver, RCVR-3S, this may not be necessary. However, to operate the RCVR-3S in the manner described above would require extensive changes to it, especially if the PL's transmitted signal were to be synchronized accurately to GPS time. For example, the RCVR-3S will not share a frequency standard, nor will its antenna electronics (AE-4) share its antenna. The AE-4 also will not accept a blanking signal. However, under the cost goal guidelines provided for shipboard installation, this blanking pulse may be a desirable feature to add.

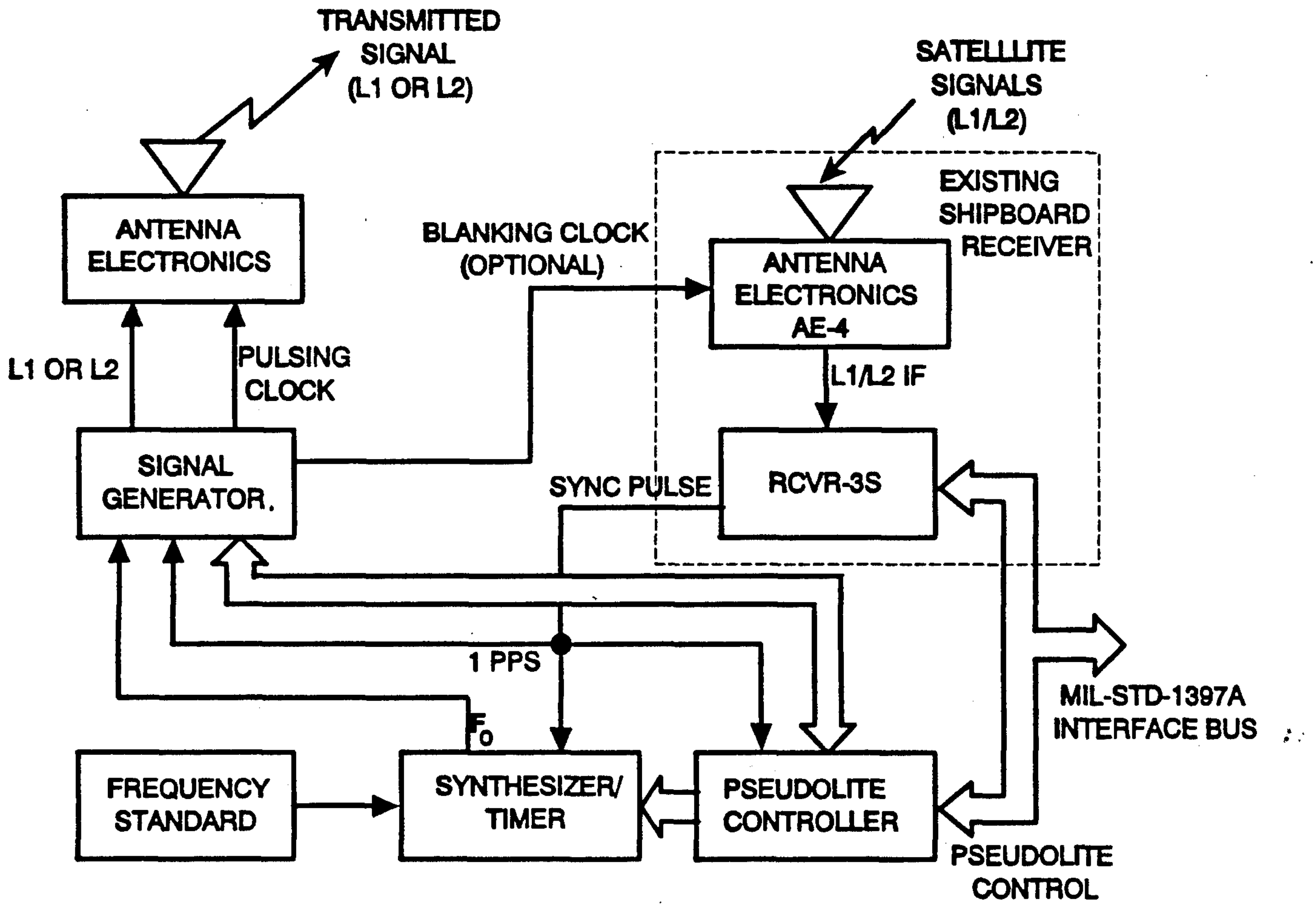

Figure V.2. RCVR-3S/PL Concept

Without an ultimate accuracy requirement, to be synchronized to the same time and frequency source and to use the same antenna would not be necessary. However, it might be necessary to have a GPS receiver track the PL generated signal for integrity purposes. It will be shown later that the RCVR-3S should be able to track the PL signal with software modifications. If not, the PL may still be required to contain a receiver, but one with a reduced capability, such as the capability to track only one signal. If timing accuracy were not critical, it may suffice to simply synchronize the PL's time to a time pulse output of the RCVR-3S. This would provide sufficient accuracy for signal acquisition purposes.

For the distances to the airborne users in this application, it suffices for the PL to transmit on only one frequency. One would think that it would be more appropriate that this be the GPS L1 frequency, primarily because the satellite L1 signals are 3 dB stronger than the satellite L2 signals, providing 3 dB more interference margin. However, in order to get adequate range to the airborne users (say, 300 nautical miles), the L1 signal from the PL suffers from more space loss, so a stronger signal must be transmitted. As is turns out, the 3 dB advantage is minimal. Since the L2 signals from the satellites are never used for acquisition (no C/A code), and since it is a secondary signal used primarily for ionospheric delay corrections, it may be more appropriate to transmit on the L2 frequency. For the purpose of the analysis provided below, the L2 frequency will be used.

Also, in the case of this DGPS application, it is appropriate for the PL to only transmit the GPS P code, because the airborne GPS receivers will already have been navigating with GPS when entering the area. These receivers will not have a need for coarse acquisition of the PL signal, because the state of the received PL P code will be fairly well known, and the receivers can acquire it directly. Another reason for not using the C/A code is that it is much more susceptible to cross-interference between the PL and the satellite signals, and between different PLs.[3]

More detailed discussions related to the implementation of the PL appear in Section 2.8 describing the derivation of shipboard equipment requirements.

V.3 Signal Analysis Solving the near-far problem is basically the subject of the references in Footnote 3 for the civil applications of PLs, which is similar to the problem addressed here, but much worse because the civil community is forced to use the C/A code. The problem stems from the fact that the received GPS satellite signal power (L2 in this case) is nearly constant at a level of -136 dBm, while the received PL signal power varies inversely proportional to the square of the distance to the PL. Thus, if the PL transmitted power is set for reception at -136 dBm at some distance d_o, the received PL signal power at some other distance d is

$$P_r = -136 \text{ dBm} + 20 \log_{10}\left[\frac{d_o}{d}\right] \qquad \text{(V.1)}$$

For example, if a PL is designed for a reception of -136 dBm at 300 nautical miles (NM) (d_o), at 0.1 NM (d) its received power level is -66.5 dBm, 69.5 dB stronger than the nominal received GPS satellite signal power. This could create all sorts of problems with the acquisition and tracking of the GPS satellite signals due to interference and cross correlation between the PL's P code signals and the satellite P code signals.

V.3.1 Evaluation of the Interference Problem It is important that interference caused by PL signals to military receivers in general be minimized, especially to receivers that are not taking part in this DGPS application. Then, at the same time, the problem will also be minimized for DGPS participating receivers. Before evaluating the interference problem, let us first take advantage of the work the civil community did to define a signal structure that did minimize the interference problem, even if that work was related to the C/A code. The most important output of that work was the definition of a PL signal that is pulse modulated with a certain duty cycle, so that it only interferes with the satellite signals for a small percentage of the time. The following evaluation makes that basic assumption.

---

[3]A. J. Van Dierendonck, "The Role of Pseudolites in the Implementation of Differential GPS", Proceedings of PLANS '90, IEEE Position Location and Navigation Symposium, Las Vegas, NV, March 20-23, 1990.

T. Stansell, Jr., "RTCM SC-104 Recommended Pseudolite Signal Specification, Global Position System, Volume III, The Institute of Navigation, 1986.

V.3.1.1 Interference Ratios Independent of the effective range of useful PL signal reception, there is some distance from the PL where signal limiting will occur in a GPS receiver, independent of the receiver's design and implementation. One such implementation may include a precorrelation wideband Automatic Gain Control (AGC), that will suppress pulses down to the level of that it is maintaining as the ambient noise floor. This is the implementation used in the MAGR and the RCVR-3A and 3S.[4] Yet another implementation is in the form of a precorrelation analog-to-digital (A/D) converter in a digital implementation, one that follows a relative narrowband AGC and saturates when the pulses appear, and effectively clips them. The MAGR has both a wideband AGC and an A/D converter, so it suppresses pulses until the AGC saturates, and then clips the pulses in the A/D converter.

Wideband AGC Effects The advantage of the wideband AGC approach is that the pulses are "almost" hard-limited. The effect is that the pulses "punch" holes in the received satellite signals, causing a reduction in the satellite signal received power proportional to the duty cycle of the pulses, which in this case can be relatively small. Of course, that implementation is not perfect. The AGC circuit does not respond instantly, so there will be some portion of the pulse being passed through the correlators due to transient AGC loop response. Also, because the AGC only has a finite dynamic range, part of the strong pulses will still pass through, up to the level where the receiver's front end saturates. Pulses transmitted from a PL can be that strong if the receiver is close enough to the PL. Of course, this would always be the case for the shipboard GPS receiver, unless signal blanking were provided. Figure V.3 presents how much the pulses might exceed the dynamic range of the AGC, as a function of duty cycle and distance from the PL for an L2 frequency signal whose power level is set for reception at 300 NM. This is based on the RCVR-3S and the AE-4 specifications.[5] The RCVR-3S specification specifies a maximum IF input of -51dBw. The AE-4 specification specifies a total gain of 37 ± 5 dB. Taking into account cable loss, an assumed gain of 37 dB results in the AGC upper limit, referenced to the AE-4 input, to be -88 dBw.

The Navy's version of the MAGR, on the other hand, does not use the AE-4.[6] The antenna electronics are imbedded into the unit itself, with a 1 dB gain compression point greater than -72 dBw. Its AGC also has a much higher dynamic range, indicated to be approximately 70 dB.[7] As will be shown later, however, that it makes very little difference in the case of the MAGR, primarily because it is a digital receiver that naturally clips the pulses at a relatively low level.

---

[4]G. B. Frank and M. D. Yakos, "Collins Next Generation Digital GPS Receiver", Record of PLANS '90, IEEE Position Location and Navigation Symposium, Las Vegas, NV, March 20-23, 1990.

John W. Murphy and Michael D. Yakos, "Collins Avionics NAVSTAR GPS Advanced Digital Receiver", Proceedings of the Institute of Navigation National Aerospace Meeting, Arlington, VA, March 22-25, 1983.

J. F. Vacherlon, et al, "GPS Phase III Multi-Channel User Equipment", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

In the first reference of the previous footnote, an erroneous assumption was made with respect to the RCVR-3A and 3S. In the writting of that paper, the use of the wideband AGC in those receivers was not known, and it was assumed that limiting was applied at a 10-15σ level, where σ is the amplitude of the RMS noise floor. However, the results of that paper are still correct, because saturation (or clipping) still occurs when close to the PL.

[5]Prime Item Development Specification for the R-2331/URN Radio Receiver of the User Segment NAVSTAR Global Positioning System, CI-RCVR-3011A, 21 March 1988.

Prime Item Development Specification for the AM-7134/URN Antenna Electronics Amplifier of the User Segment NAVSTAR Global Positioning System, CI-AE-3061A, 21 March 1988.

[6]Specification for NAVSTAR Global Positioning System (GPS) Miniature Airborne GPS Receiver (MAGR), Final Draft, Specification Number CI-MAGR-300, Code Identification 07868, 30 March 1990.

[7]G. B. Frank and M. D. Yakos, "Collins Next Generation Digital GPS Receiver", Record of PLANS '90, IEEE Position Location and Navigation Symposium, Las Vegas, NV, March 20-23, 1990.

The received pulse power plotted in Figure V.3 is

$$P_{pr} = -136 \text{ dBm} + 20 \log_{10}\left[\frac{d_O}{d}\right] - 10 \log_{10} \text{PDC} \qquad \text{(V.2)}$$

where PDC is the pulse duty cycle -- the ratio of the time signal is transmitted to total time. In this equation, as in Equation V.1, the received power is that at the input to the receiver, not at the antenna. It is assumed here that the transmitted power is adjusted to account for the average antenna gain of the airborne platforms.

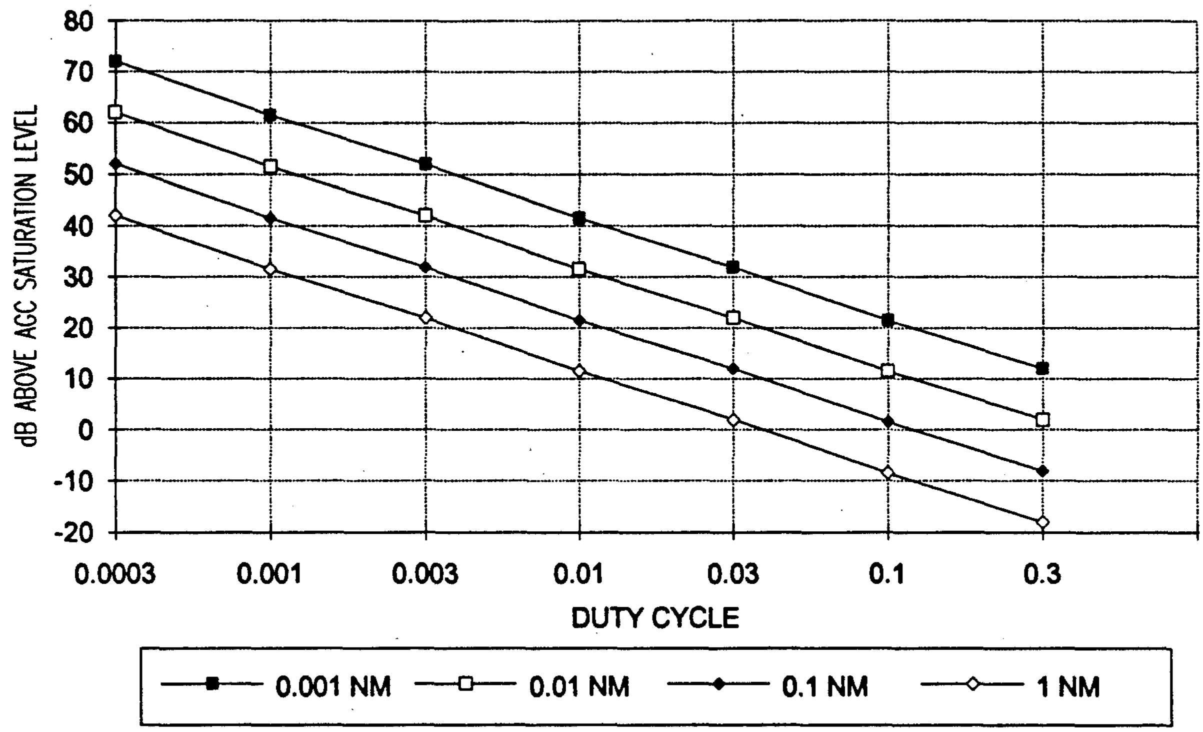

Figure V.3. Received PL Pulse Power Relative to AGC Dynamic Range

Narrowband AGC Effects Coupled with Digital Quantization The limiting A/D converter on the other hand, coupled with a narrowband AGC, is typical in some modern digital receiver implementations. In this case, the strong pulses would always be clipped, no matter how strong they were, since the AGC wouldn't respond to them, and the receiver would operate on the "clipped" pulses. A wideband AGC coupled with digital quantization, such as is the implementation in the MAGR, has the same effect after the AGC saturates. The only difference is that clipping occurs at much higher received power levels. After saturation, the AGC essentially has an infinite time constant.

In observing Figure V.3, one might ask why should a lower duty cycle be used when, in order to achieve the required average reception power, saturation occurs quicker than for higher duty cycles. The answer is in the analysis that lies ahead, which shows that less satellite power is lost with lower PL duty cycles.

Whether a wideband or a narrowband AGC is used, it is only necessary to evaluate the worst case situation where the PL power seen by the receiver's correlator is the power of the saturated or clipped signal. For the purposes of evaluating the interference of the PL signals with the satellite signals, only the relationship of that limited signal power to the received GPS satellite signal power is important. That relationship, in dB, is

$$P_L = 10 \log_{10}(N^2B) + N_O - S \qquad \text{(V.3)}$$

where N is the number of sigma above the ambient noise at which the limiting occurs in bandwidth B, N_0 is the noise density in dB/Hz and S is the received satellite signal power. The power P_L is peak power rather than average power, making it independent of the pulse duty cycle, except for the fact that the satellite signal is lost while limiting occurs. However, for reasonably low duty cycles, that loss is much less than a dB. This expression also does not hold for the true hard-limiter (1-bit sampling) case, but then, no military receiver could tolerate CW jamming with that sort of design. Values of $\frac{P_L}{S}$ are plotted in Figure V.4 for both the L1 and L2 signals as a function of how much the PL signal exceeds the dynamic range of the AGC or the A/D converter, and for a bandwidth B of 26 MHz, the bandwidth of the RCVR 3A and 3S. A 4.25 dB receiver noise figure is assumed, based on the AE-4 specification.

In the case of the MAGR, the bandwidth is limited to 20 MHz, so the values of $\frac{P_L}{S}$ for it will be about 1.14 dB less. Of course, the value of N for the MAGR is limited by the A/D converter. It's A/D converter has two thresholds, outputting to the correlator, either a +1, 0 or a -1, where the 0 occurs when the input signal is between the two thresholds. For Gaussian noise, that assumed when the PL signal is not present, the thresholds are optimally set so that the ±1's would occur about 40% of the time. If a strong pulse occurs after the AGC limits, the ±1's essentially occurs all the time. This results in an N of $\sqrt{\frac{1}{0.4}} = \sqrt{2.5} = 1.581$. This equivalent to an AGC saturation point of 4 dB above ambient noise. The only time this isn't true, is when the pulses are below the ambient noise, which is a non-problem using low duty cycles, or if the pulse is controlled by the AGC to produce ±1's 40% of the time. As will be shown, that case is also a non-problem using low duty cycles.

Thus, although the X-axis of the plot is labeled as dB above AGC dynamic range, the 4 dB value is typical for digital MAGR receiver. The pulses are actually attenuated by 1.17 dB in the MAGR, RCVR 3A and 3S by the wideband limiting AGC that follows the pulses until the AGC dynamic range is exceeded. The larger values on the X-axis would occur when that dynamic range is greatly exceeded, limited by the dynamic range of the receiver's front end.

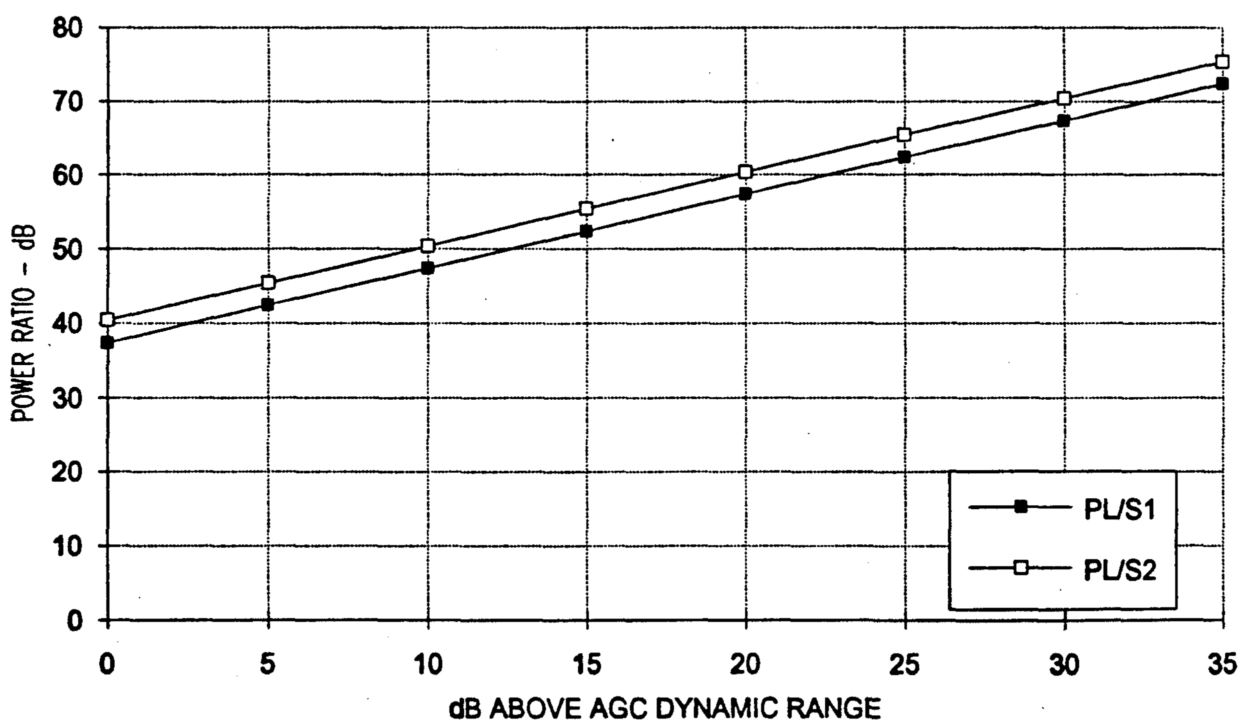

Figure V.4. Ratio of PL Power to Received Satellite Signal Power at the Correlator

V.3.1.2 Loss in Satellite Signal-to-Noise Not taking into account the momentary cross correlation between the received PL and satellite signals, the PL received signal appears to be a pulse jammer to the GPS receiver when acquiring or tracking a weaker satellite signal. However, as described above, a receiver designed to operate in a pulsed jamming environment either clips the pulses or suppresses them, averaging any residual over time. The result is a loss in effective satellite carrier-to-noise density $\frac{C}{N_o}$, which is shown versus that residual (in dB above AGC dynamic range) for different duty cycles in Figure V.5. The PL power output is set so that its received power equals that of the satellite at 300 NM, the assumed range of the Shipboard TACAN Replacement system. In general, the effective average signal-to-noise ratio is given as

$$\frac{S}{N_o\text{eff}} = \frac{S(1\text{-PDC})}{N_o\left[1 + \frac{2}{3}N^2B\bullet PDC\right]} \qquad \text{(V.4)}$$

The numerator of this equation represents the reduced signal power due to the "hole punching". The denominator represents the increase in post-correlation noise density due to the average cross-correlation with the pulsed, but limited, PN code PL signal. The $\frac{2}{3}$ factor is due to the fact that the "jammer", as seen by the correlator, has the same spectral density and bandwidth as the reference code. If it were a pulsed CW signal, that factor would not apply. Note that the ratio $\frac{S}{N_o}$ appears in the right-hand side of the equation. Thus, the rest of that term represents the loss. Thus, Figure V.5 is simply the plot of

$$L = -10\log_{10}\left[\frac{1\text{-PDC}}{1 + \frac{2}{3}N^2B\bullet PDC}\right] \qquad \text{(V.5)}$$

versus 10 $\log_{10}(N^2B)$. Because of that, the plot is independent of receiver bandwidth.

Note that if the AGC dynamic range is not exceeded, or if a saturating A/D converter implementation is used, the losses due to the pulses is reasonable for all duty cycles, although definitely much better at the lower duty cycles. However, if the AGC dynamic range is exceeded, which occurs when close to the PL, lower duty cycles are probably required. It should be pointed out, however, that losses are respect to ambient noise conditions, and that the military receivers are expected to operate in jamming environments. For example, both the RCVR 3A and 3S are required to operate in P code modes under minimum continuous J/S conditions of 40 dB, which typically results in a loss of satellite $\frac{C}{N_o}$ on the order of 5 or 6 dB with respect to ambient conditions.

The AE-4 specification indicates a requirement for a 1 dB gain compression point of greater than -74 dBw at the input as measured from the RF input to the IF outputs at L1 and L2. This is the point at which the RF/IF gain deviates by no more than 1 dB from being linear in dB. Usually, saturation occurs within 4 or 5 dB of that point, or at a point of -70 dBw. If one couples that with the maximum AGC limit of -88 dBw referenced to the AE-4 input as derived above, the receiver front-end (AE-4) would saturate somewhere around 18 dB above the level at which the AGC would saturate. Thus, from Figure V.5, this would indicate that any duty cycle less than $\frac{1}{64}$ would be acceptable with minimal loss of SV $\frac{C}{N_o}$.

Figure V.5 is the average loss in general that would occur in the RCVR-3A or the RCVR-3S. Since the MAGR's A/D converter "clips" the pulses its loss will be limited to that shown in Figure V.6 as a function of duty cycle. Note that the loss is not significant at any plotted duty cycle in the MAGR receiver.

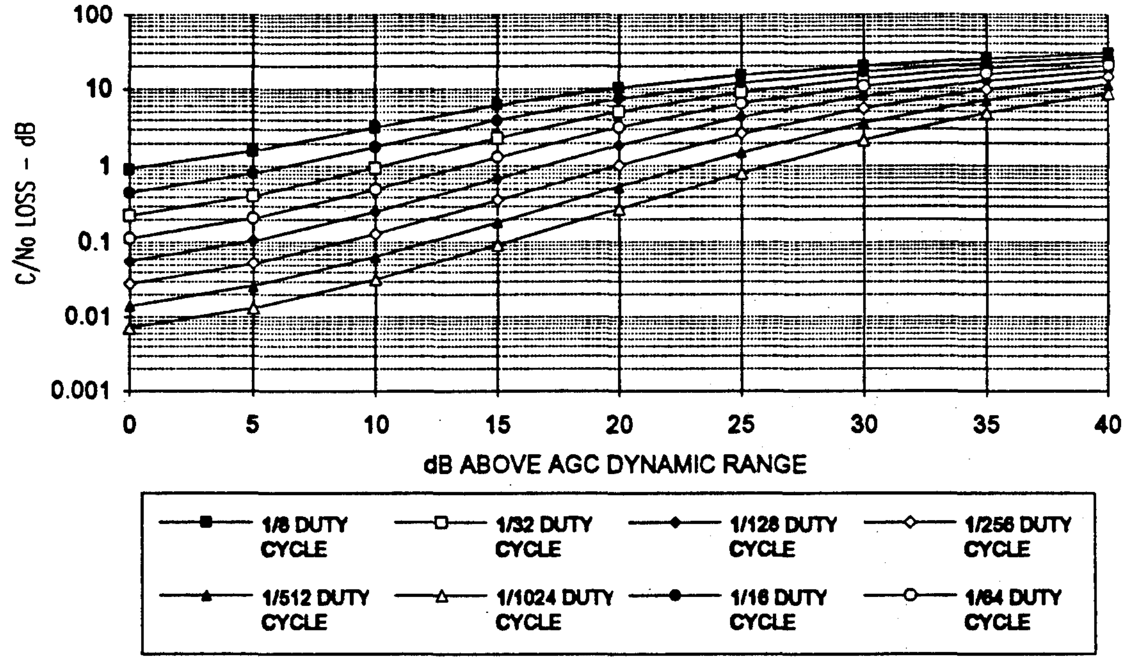

Figure V.5. Loss of Satellite C/N_0 due to Pulsed PL Signals

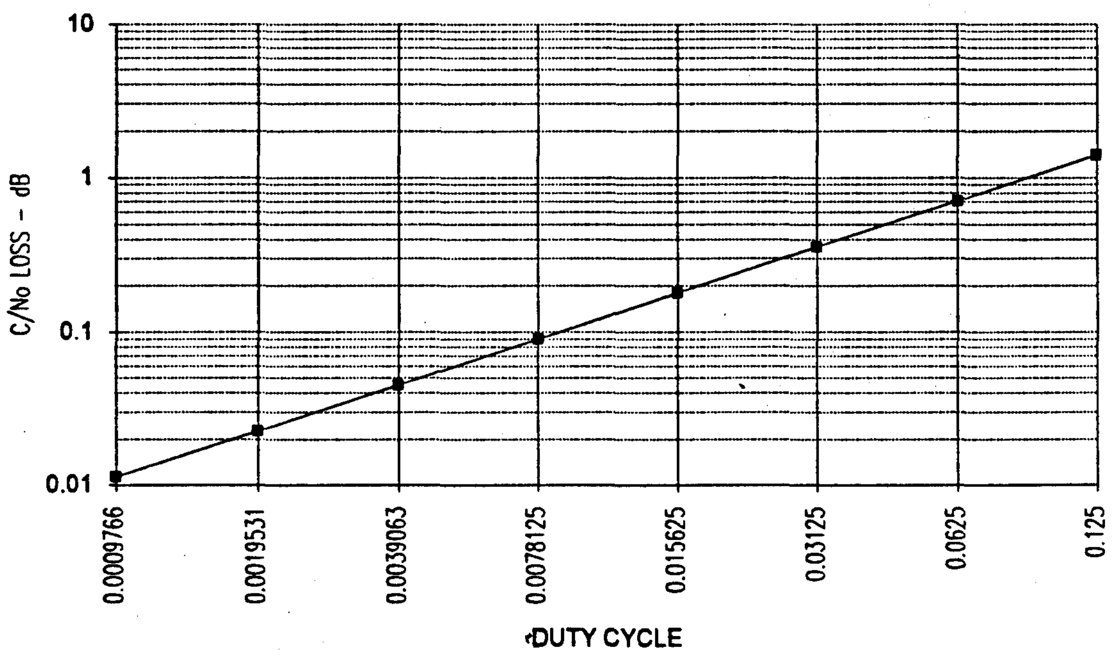

Figure V.6. Loss of Satellite C/N_0 due to Pulsed PL Signals in the MAGR Receiver

V.3.1.3 Cross Correlation Ratios The above discussions present the average loss in satellite $\frac{C}{N_o}$. In addition to that loss, one must consider a temporary cross correlation level that could possibly cause false alarms or loss of lock when acquiring or tracking a satellite signal due to the reception of a strong PL signal. Given the ratios of effective received PL to satellite powers presented in Figure V.4, it is now appropriate to evaluate the cross correlation power ratios of the P codes as a function of duty cycle, given, at least for the moment, that the signal power of all P codes are the same.

The question is, "What is a correlation or cross correlation level?". The answer is that, while the correlation process is occurring (exclusive or-ing a reference code against a received code), the correlation level is the sum of all code chips that agree minus those that disagree over a specific summation interval, divided by the number of chips in the interval. The negative of that is also true (disagree minus agree) because the result of the summation is squared to obtain energy over the summation interval. The most simplistic case occurs if the interval is one chip, in which case the correlation level is always at its maximum level.

In the case of P codes, correlation never occurs over the entire code, so correlation over a partial code is always the case, even if the received code and the reference code are lined up exactly, and even if the entire code over that period is received (no pulsing). Since coherent integration in the subject GPS receivers is usually between 1 millisecond (ms) and 20 ms,[8] let us assume the "entire" code cases to be 10,230 chips and 204,600 chips for the 1 ms and 20 ms cases, respectively.

In the case of correlating over partial codes, we must use the basic definition of level -- agree minus disagree or disagree minus agree divided by total number in an interval -- and the probability of each level occurring in that interval. We can then derive the mean, variance and RMS of the resulting cross correlation power level in that interval. If the interval is short with respect to the length of the code, we can basically assume that each chip pattern over the interval occurs with equal probability. For example, over a period of 3 chips, each of the 8 chip patterns can occur in each code with a probability of $\frac{1}{8}$. Then, in general, over M chips, there are 2^M chip patterns, each with a probability of 2^{-M}. The corresponding absolute correlation level if K chips agree of the M chip interval is then

$$C_{KM} = \frac{|2K-M|}{L};\ K = 0,1,\ldots,M-1 \qquad \text{(V.6)}$$

where it is assumed that M chips occurred in an interval containing L chips of an satellite's P code. That is, for a duty cycle of $\frac{M}{L}$, the maximum absolute correlation level is $\frac{M}{L}$ (K=0, which is the same as K=M). The probability P_{KM} of an absolute correlation level is

$$P_{KM} = \begin{pmatrix} M-1 \\ K \end{pmatrix} 2^{1-M} \qquad \text{(V.7)}$$

with an average cross correlation power over an L chip interval of

[8] Computer Program Development Specification for the Receiver Pre-Processor CPCI of the User Segment User Equipment NAVSTAR Global Positioning System, Specification Number CP-RPP-2516. Code Identification 13499, 31 July 1981.

Jeffrey C. Rambo, "Receiver Processing Software Design of the Rockwell International DoD Standard GPS Receiver", Proceedings of ION GPS-89, The Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, CO, September 27-29, 1989.

$$\mu_{cp}(M) = \sum_{K=0}^{M-1} C_{KM}^{2} P_{KM} \qquad \text{(V.8)}$$

Evaluating this by deduction results in

$$\mu_{cp}(M) = \frac{M}{L^2} \qquad \text{(V.9)}$$

The variance of the cross correlation power can be derived similar to the average, resulting in

$$\sigma_{cp}(M) = \frac{\sqrt{2M(M-1)}}{L^2} \qquad \text{(V.10)}$$

The resulting evaluation of partial cross correlation power is shown in Figures V.7 and V.8 in dB below full correlation versus duty cycle for the 1 ms and 20 ms coherent integration intervals, respectively. The resulting duty cycle is also shown in dB. Curves for mean, mean plus 3 sigma and rms cross correlation power are shown, allowing evaluation against either of those criteria. As expected, the 20 ms case is simply 13 dB lower than the 1 ms case. Also note that the cross correlation power for a duty cycle of 1 is simply the inverse of the length of the code over the integration interval.

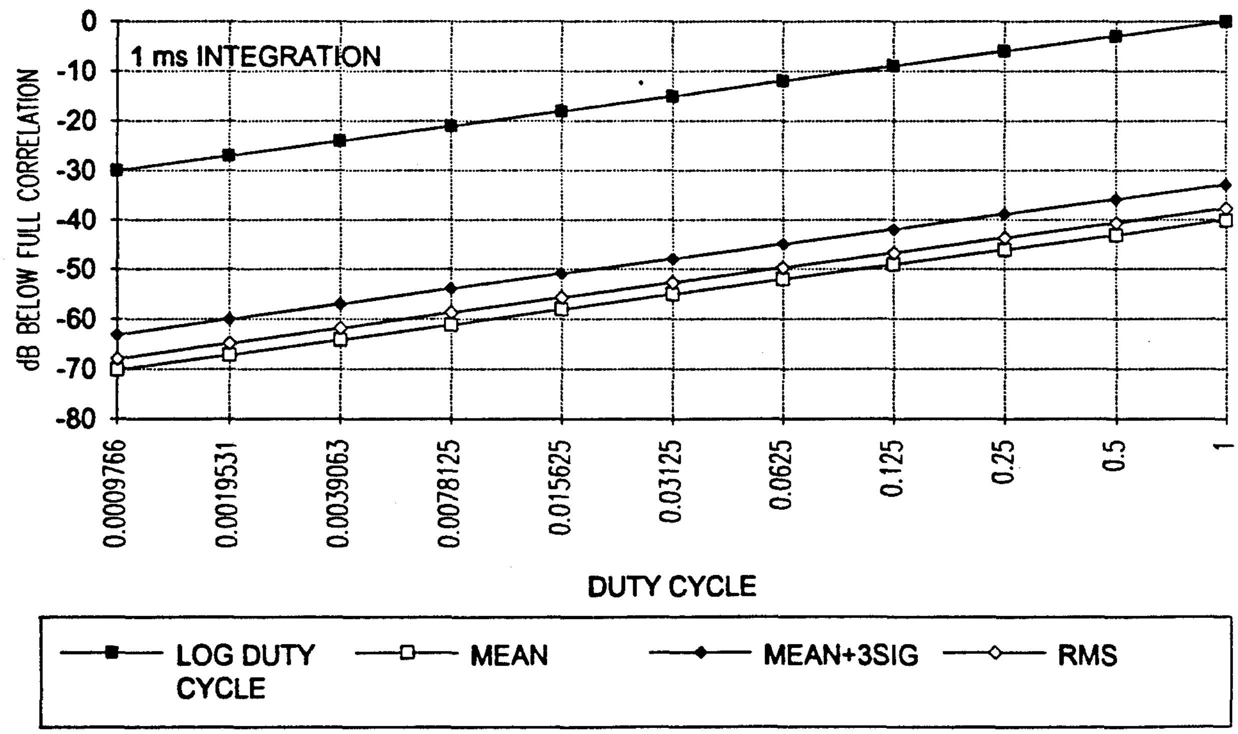

Figure V.7. P Code Cross Correlation Power in a 1 MS Interval

Receiver Processing Considerations First, let us evaluate the meaning of the curves in Figures V.7 and V.8. Again, these curves indicate the relative power obtained via the correlation process from one P code signal when trying to correlate to another, coherently measured over a 1 millisecond and a 20 millisecond interval, respectively. The 1 ms coherent integration represents a measurement in a 1 kHz predetection noise bandwidth, while the 20 ms coherent integration represents a measurement in a 50 Hz predetection noise bandwidth. Now, the MAGR, the

RCVR-3A and the RCVR-3S do, at times for wideband acquisition, measure power over a 1 millisecond interval, but they do use it. Instead, they add up a minimum of 20 of those power measurements to represent total power in a 1 kHz bandwidth measured over a post-detection interval of at least 20 ms.[9] The effect of this is to reduce the cross correlation power of Figure V.7 by at least a factor of 5 $\log_{10}(20)$, or 6.5 dB. This is because the P code is uncorrelated from one 1 ms interval to the next, so that the cross correlation noise, although squared, is smoothed over those 20 samples while the satellite signal power is directly additive over that same interval. (This is not the case for the C/A code, which is an additional problem for civil users of PLs.[10] In the C/A code case, the cross correlation noise in successive 1 ms intervals is highly correlated because the code repeats every millisecond.) Thus, when using the P code, the situation isn't as bad as the figure presents.

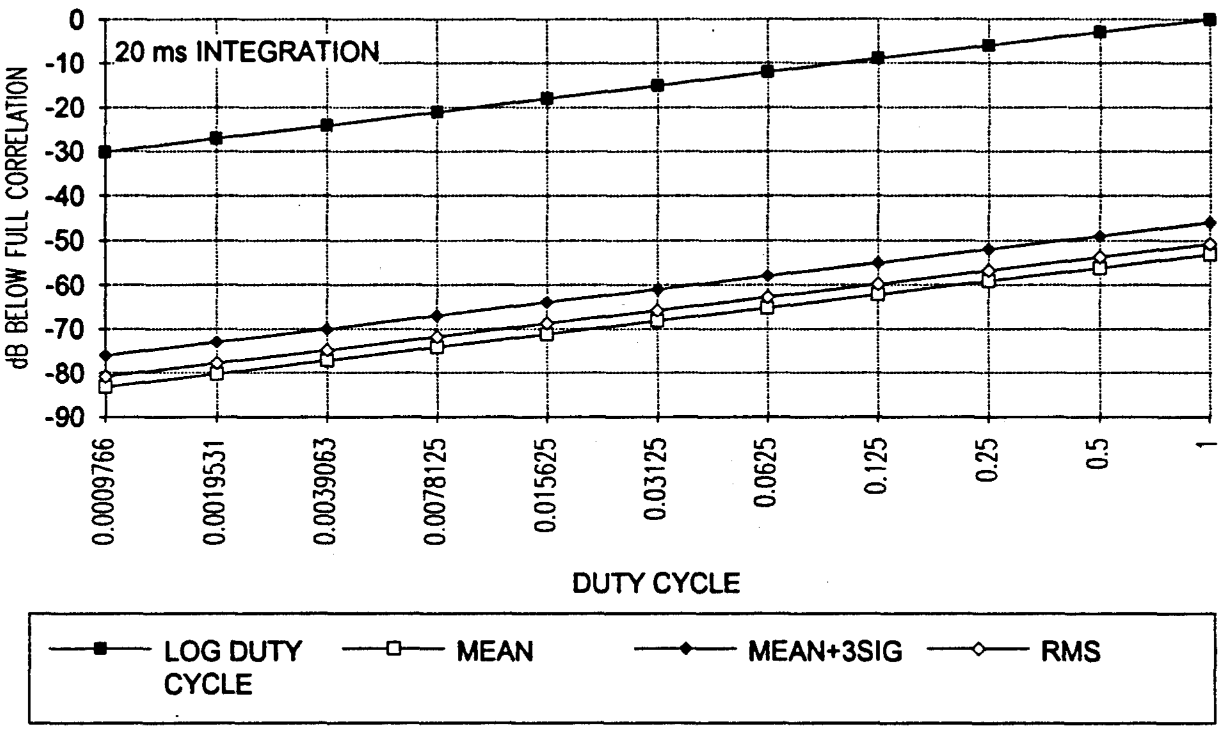

Figure V.8. P Code Cross Correlation Power in a 20 MS Interval

This 20 ms sum of 1 ms power measurements is a typical operation in the MAGR, the RCVR-3A and the RCVR-3S during a wideband satellite signal acquisition. However, because of jamming considerations, a 1 ms predetection integration interval is the minimum used. For most P code modes, the predetection integration intervals are usually longer than that because of the jamming requirements imposed. The indication is that the post-detection interval is always 20 ms.[11] Likewise, tracking loop bandwidths are always less than that 50 Hz post-detection bandwidth. Thus, during tracking, the situation is always better that Figures V.7 and V.8 represent, usually by a factor of 5

[9] See reference under previous footnote.

[10] A. J. Van Dierendonck, "The Role of Pseudolites in the Implementation of Differential GPS", Proceedings of PLANS '90, IEEE Position Location and Navigation Symposium, Las Vegas, NV, March 20-23, 1990.

T. Stansell, Jr., "RTCM SC-104 Recommended Pseudolite Signal Specification, Global Position System, Volume III, The Institute of Navigation, 1986.

[11] Jeffrey C. Rambo, "Receiver Processing Software Design of the Rockwell International DoD Standard GPS Receiver", Proceedings of ION GPS-89, The Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, CO, September 27-29, 1989.

$\log_{10}(B_L/50)$, where B_L represents the tracking loop bandwidth. This is in addition to the 6.5 dB improvement stated earlier for the 1 ms predetection intervals. These factors should be considered when evaluating the cross correlation margin. For example, that reference indicates that the carrier loop bandwidth is 5.8 Hz with a predetection bandwidth of 50 Hz. Thus, the cross correlation power for that case is reduced by 5 $\log_{10}(5.8/50)$, or 4.7 dB, with respect to that shown in Figure V.8.

V.3.1.4 Cross Correlation Margin Figures V.9 and V.10 are plots of the values in the plots of Figures 7 and 8 are added to the values of the plot for $\frac{P_L}{S2}$ in Figure V.4 to evaluate the cross correlation problem for a 20 ms interval. Figure V.9 takes into account the post-detection improvements for the 1 ms case described above (6.5 dB). Of course, Figure V.10 is shifted exactly 6.5 dB from Figure V.9. The result is cross correlation margin versus dB above the AGC dynamic range for the RCVR-3A and RCVR-3S cases. The evaluation of those plots at 4 dB above the AGC dynamic range is the only case of interest for the MAGR receiver because of A/D converter clipping. Then, this cross correlation margin should be traded off against an appropriate duty cycle, given the AE-4 saturation level for the RCVR-3S and RCVR-3S, indicated to be around 18 dB above the AGC dynamic range.

Note that for the MAGR, any duty cycle would be acceptable. For the RCVR-3A and RCVR-3S, any duty cycle less than or equal to $\frac{1}{128}$ should be acceptable, provided that the AE-4 saturates at 20 dB or less above the AGC dynamic range.

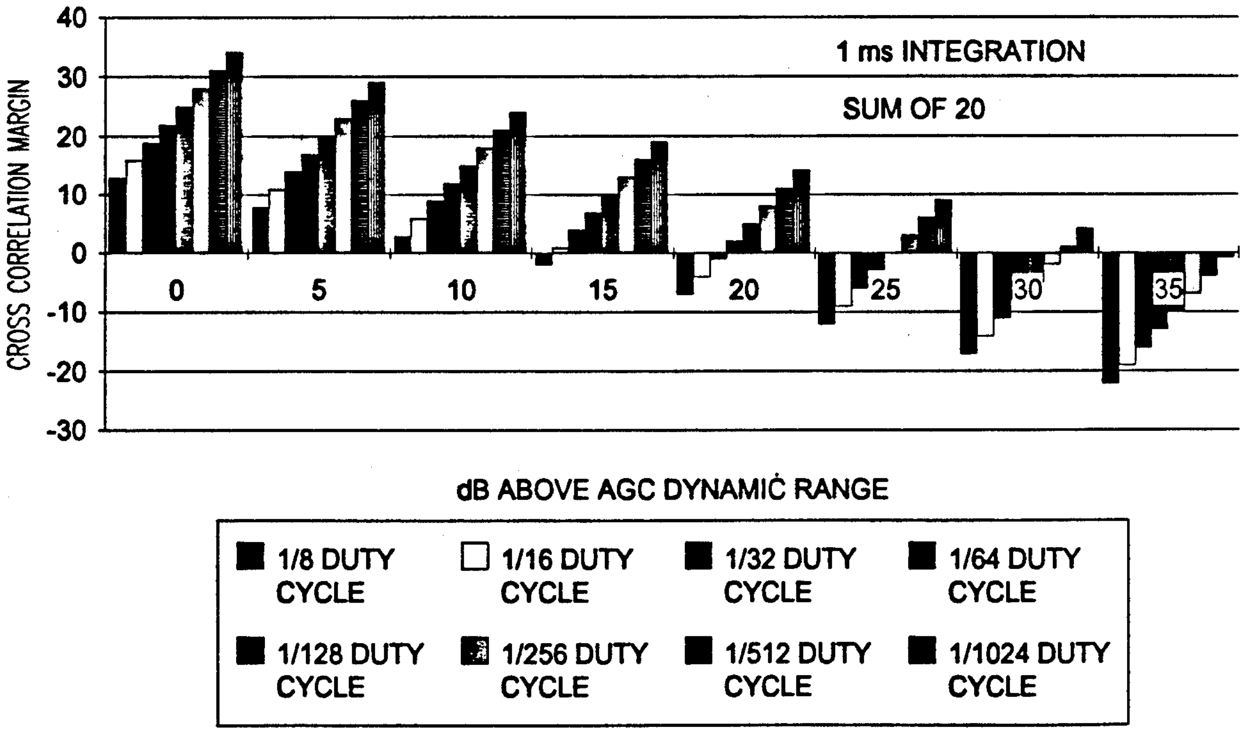

Figure V.9. Cross Correlation Margin for a 1 ms Predetection Integration Interval

V.3.1.5 Another Technique for Improving Cross Correlation Margin Another technique for improving cross correlation margin is to offset the PL's frequency a moderate amount so that the received PL doppler frequency will never correspond to a received satellite doppler frequency. This doppler offset would only have to be on the order of 10 - 15 kHz, but the larger the better. Then, the received PL signal would then never be in the predetection bandwidth (<1 kHz) of the received satellite signal, and would be attenuated by predetection filtering. For a coherent integration interval T_I, this attenuation is at least 10 $\log_{10}N$, where N is the multiple of $\frac{1}{T_I}$ bandwidths equal to the offset. For example, if T_I is 1 ms, and the offset is 10 kHz, N is 10 and the minimum attenuation is 10 dB. The same offset would result in 23 dB if T_I is 20 ms.

The last reference in Footnote 4 indicates that the RCVR-3A and the RCVR-3S carrier VCO can handle offsets as high as 21.3 kHz. Thus, including airborne receiver to ship doppler, this additional margin is feasible, and increases the already adequate margins. The MAGR has a much higher doppler capability. Thus, for it, this frequency offset is a non-problem.

It is important to note, however, that this technique will not reduce the average C/N_0 loss shown in Figure V.5, since that is due to the spread PL signal, which applies to any doppler within the P code bandwidth. Cross correlation is when the PL signal is not completely spread and the residual correlated portion does have a doppler frequency component. It is also important to note that, because of code repetition, this property does not necessarily apply to the C/A code.

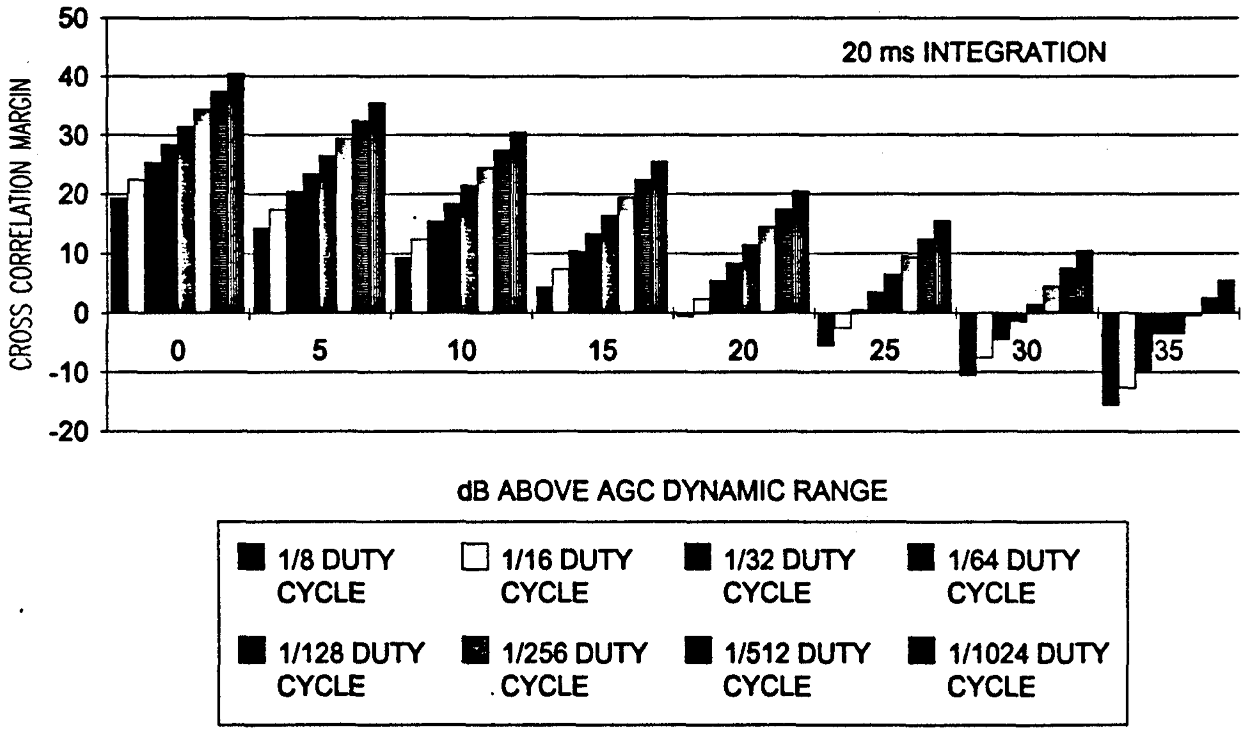

Figure V.10. Cross Correlation Margin for a 20 ms Predetection Integration Interval

V.3.1.6 Interference to the Satellite C/A Codes If the PL uses the L2 frequency, this is not a problem. If the PL uses the L1 signal, the interference of the PL P code signal with a satellite's C/A code signal is 13 dB less than with the satellite P code signal. This is because the satellite C/A code is 3 dB stronger than its P code signal, and the C/A code correlation bandwidth is 10 times narrower than the P code bandwidth. Thus, the values in Figure V.5 would be reduced by 13 dB with respect to the $\frac{P_L}{S1}$ power ratio.

V.4 Proposed PL Signal Structure The following parameters must be defined to specify the PL signal structure for the Shipboard TACAN Replacement system:

1) P code PRN number

2) Pulse duty cycle (PDC)

3) Pulse repetition frequency (PRF) and pulse width (PW)

4) Transmitted power

5) Pulse pattern (i.e. time position of pulses)

6) Frequency and frequency offset

7) Signal Encryption

These parameters are defined here. Some of the parameters are highly related and are defined together.

V.4.1 P Code PRN Number ICD-GPS-200B defines five PRN numbers, 33 through 37, as being reserved for uses other than satellites (e.g. ground transmitters).[12] Thus, these PRN numbers could be used for the subject system, but there are not enough of them. However, many PRN numbers can be derived from those five by simply slicing them up in time. Essentially, that is what was done for the satellite codes, plus these five codes. Actually, the P code is one long code that is 38 weeks long. For the 37 codes, it was partitioned into 37 one week codes with gaps between them, and they reset at the end of the week.

As it turns out, using hind sight, there is no reason why these individual codes ever had to be so long. They could have just as well made them, say, only one hour long, since a receiver could never acquire the code in a reasonable time anyway with that kind of time uncertainty. Thus, we could break up these five codes into 840 one hour codes (or more), by simply assigning a PRN code number, plus a time of week to each one. Actually, it would be best not to break up the codes similar to the way the 37 codes were, because they would have to be reset at the end of the one hour period. It would be better to simply assign a code plus a delay. That is, PL #1 would be assigned the code 33 with no delay, PL #2 assigned code 33 with a one hour delay, ... PL #168 assigned code 33 with a 167 hour delay, PL #169 assigned code 34 with no delay, etc, up to PL #840 assigned code 37 with a 167 hour delay. This way the codes would only have to be reset at their natural end-of-week, which would not necessarily be the end of the GPS week. They would just simply be initialized with a different time.

Using this technique for assigning codes requires no hardware changes to GPS receivers or transmitters, and would satisfy any requirement for sharing the five available codes with other systems as well as all the shipboard PLs.

V.4.2 Pulse Duty Cycle Pulse duty cycle is related to the pulse repetition frequency (PRF) and the pulse width (PW) as

$$PDC = PRF \times PW \tag{V.11}$$

For example, a PRF of 1000 pulses per second and a PW of 1 microsecond results in a PDC of 0.001. The actual values of these parameters would be a tradeoff that is a function of pulse width, which would affect PL power amplifier design. This will be addressed below.

V.4.3 Pulse Repetition Frequency and Pulse Width Given the PDC, these two parameters have to be defined together, although the PL power amplifier design is more sensitive to PW. The PRF doesn't really make any difference from a design point of view. It will only affect the duty cycle. PRF may have some effect on the response of the receivers' AGC, but that is doubtful.

The PW should be an integer number of P chips in time to simplify pulse clocking, as should the time between pulses that defines the PRF. This is easy enough to achieve. Both receiver and transmitter designs are sensitive to the actual value of PW, however. Narrow pulses may be hard to implement in power amplifiers because of on-off

---

[12] Navstar GPS Space Segment\Navigation User Interfaces. ICD-GPS-200, Revision B, November 30, 1987.

rise and fall times. At the same time, strong, wide pulses may saturate post correlation circuitry in a receiver before they can be averaged out, dictating a requirement for narrow pulses. Thus, the tradeoff exists. From a design point of view, the PRF can be any value to meet the PDC and PW constraints.

As an example, for a strawman PRF and PW, let us select a PW of 100 P chips (9.7752 microseconds, which is 10 C/A code chips), and an average PRF of 399.60937 pulses per second (one pulse every 25600 P chips, or 256 pulse periods, on the average), resulting in a PDC of exactly 0.00390625 $\left[\frac{1}{256}\right]$. As will be discussed below, the actual time between pulses should very about this average, and making the average number of pulse periods equal to a power of two simplifies the implementation.

V.4.4 Transmitted Power The average transmitted power (P_T) of an L2 frequency PL for an average received power (P_r), through a receiving antenna with gain G_a, at a distance (d) in NM is

$$P_T = P_r + 20 \log_{10}\left[\frac{4\pi d}{\lambda}\right] - G_a = P_r + 20 \log_{10} d + 99.582 - G_a \text{ dBw} \qquad \text{(V.12)}$$

where the L2 signal wavelength λ $\left[\frac{c}{f_o}\right]$ is 0.000131863 NM. Thus, for a distance of 300 NM and a average received power of -166 dBw, the average transmitted power is -6.876 dBw, or 205.33 milliwatts, a quite moderate level. This includes an antenna gain of -10 dB, a typical value that might be realized at the line-of-sight between the PL and the airborne receiver.[13]

The peak power (P_{PK}), given a PDC, is simply

$$P_{PK} = P_T - 10 \log_{10} PDC \text{ dBw} \qquad \text{(V.13)}$$

Thus, for the strawman PDC of 0.00390625, the peak power is then 17.21 dBw, or 52.563 watts, still a quite moderate level for pulses.

Since the power amplifier need only transmit at a constant power setting, it should not be a problem to transmit these approximately 10 microsecond pulses with a peak power of 52.563 watts. Occasionally, however, it may be desirable to reduce that power level, and thus, reduce the range of reception, for LPI reasons. The rise and fall times of the pulse should be no more that about 50 nanoseconds (1/2 P chip).

Figure V.11 shows the number of P chips transmitted per millisecond and the transmitter peak power of each pulse as a function of duty cycle for the 300 NM range. Note that for even a duty cycle of 0.001 the peak transmitted power is only 210 watts.

V.4.5 Pulse Pattern The PRF of the transmission should not be constant to prevent the pulses from being received synchronous with navigation data bit edge timing received from a satellite. This can be accommodated by simply distributing the pulses uniformly with time over some time interval smaller than a bit period, as long as the average PRF is as specified. For example, the PW defined above is 100 P chips. There is an average of one pulse every 256 pulse periods, or 2.5024437 milliseconds, or an average of 7.9921875 pulses per data bit period.

It is desirable to make the pulse pattern pseudo random. This can be done by tying it to the P code, which is the reason for selecting the pulse periods to be of length 2^n pulses. Since the P code is pseudo random, one can latch

---

[13] Critical Item Development Specification for the AS-3822/URN Fixed Reception Pattern Antenna 3 FRPA3 of the User Segment NAVSTAR Global Positioning System, CI-FRPA-3070A, 11 November 1987.

E-Systems data sheet for the FRPA-3, presented by Teledyne Ryan Electronics in the Interim Design Review for the V-22 OSPREY AN/APN-217(V)5 Doppler Radar/GPS Navigation System, 18 April 1989.

the first eight code chips (bits) of a 100 chip pulse (for example), and use the eight bits to determine in which of the following 256 pulse period window the next pulse should be transmitted. In that way, the time between the leading edge of pulses will vary from 1 to 511 pulse periods, with an average of 256 pulse periods, since the average pulse position in each interval is position 128.

As it turns out, this type of pattern also allows more than one PL to operate in the same region with minimal interference between them. This is because the probability of pulses from more than one PL being received at the same time is very small, no matter what the relative geometry of the PLs is. Thus, if an airborne GPS receiver were to operate very close to one of the PLs that is suppressing its signal input during its reception, that receiver can still receive the other PL(s). Very few of the other PL(s)' pulses will be blanked out by a strong pulse from the nearby PL.

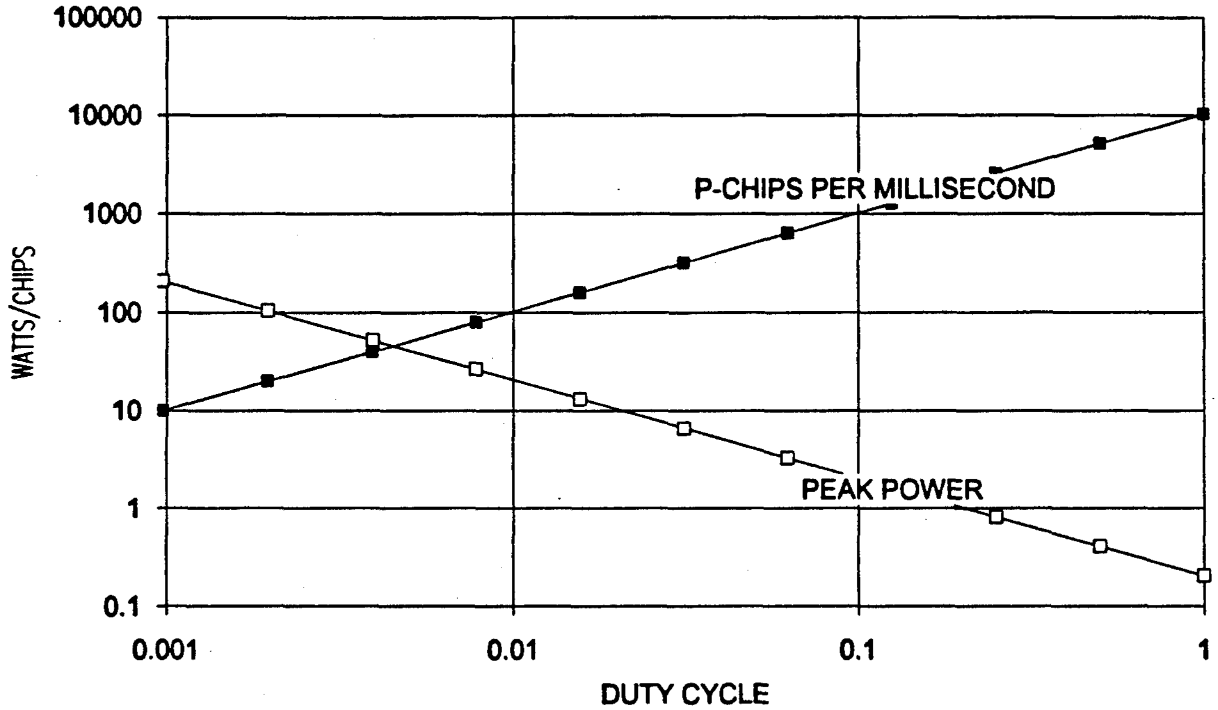

Figure V.11. Peak Power Versus Duty Cycle for a 300 NM Range

V.4.6 Frequency and Frequency Offset Since the L2 signal received from the satellites rarely includes the C/A code (only under satellite failure conditions), and would never be used for wideband acquisition purposes, the L2 signal should probably be used in the PL. In addition, as mentioned above, it makes sense to offset the carrier of the PL by 60-70 kHz to reduce the cross correlation interference with satellite signals even further. This value can be anything that is appropriate, but limited by receiver implementation range (21.3 kHz in RCVR 3A and 3S). This capability has been increased to four times that value to 85.3 kHz to accommodate spaceborne applications. This limitation has been extended to the MAGR receiver.[14] The effect of this frequency offset is to cause a doppler

[14]J. F. Vacherlon, et al, "GPS Phase III Multi-Channel User Equipment", Proceedings of the Satellite Division First Technical Meeting, The Institute of Navigation Satellite Division, Colorado Springs, CO, September 21-25, 1987.

G. B. Frank and M. D. Yakos, "Collins Next Generation Digital GPS Receiver", Record of PLANS '90, IEEE Position Location and Navigation Symposium, Las Vegas, NV, March 20-23, 1990.

Private communication with John W. Murphy of Rockwell International.

difference between satellite and PL signals, and thus, an L2 P code doppler difference of the order of 120th of that value. For example, if we were to offset the PL signal frequency by 70 kHz, the L2 P code doppler offset would be $\frac{70000}{120}$ = 583.33 chips/sec, resulting in a relative full chip change in 1.714 milliseconds. Thus, if a cross-correlation did occur, it would be gone in that period of time and averaged over the post-detection interval.

V.4.7 Signal Encryption Since the ship location information transmitted by the PL will be sensitive, the PL signal and/or DGPS data should be encrypted. Since both the airborne and shipboard GPS receivers will have the GPS Anti-Spoof capability, it is reasonable to also encrypt the P code transmitted by the PL in the same way, providing a Y code transmission. Also, it would be appropriate to use the GPS Navigation Data encryption algorithms to encrypt the DGPS data. Of course, these capabilities would have to be approved and endorsed by NSA. Since the details of this encryption capability are classified, their are beyond the scope of this study.

V.5 PL Data Structure and Format The data modulated onto the PL P code provides the airborne GPS receiver with the DGPS information required to provide the desired accuracy and flight path. To minimize the impact on the airborne receiver implementation, this data should be modulated at a rate of 50 bps to keep the demodulation techniques the same as for the satellite signals. However, if receiver software modifications are made, the data rate could be as high as 1000 bps. This is because the MAGR and the RCVR 3A and 3S all sample the receiver signal outputs at a 1 kHz rate, and could very well collect data at that rate.[15] However, for data rates much higher than about 200 bps, the transmitted power of the PL might have to be increased to ensure a reliable bit error rate in the participating receiver.

A preliminary description of the required content of the data to be transmitted appears in Section 2.3 of this report. That data content is at least a subset of the content of the 1553 Waypoint Definition Message I-4, which would define moving waypoints describing the ship's landing point trajectory, or any other intermediate RNAV waypoint. That I-4 message is made up of 26-16 bit words, or 416 bits, including waypoint mode word and waypoint number. There are 192 data bits per GPS navigation message 6-second subframe. Thus, this I-4 message would use up over 2 subframes of data. However, spare spaces in the TLM and HOW words that are used in satellite messages, but would not be required for PLs, could be used to cut the I-4 message down to 2 subframes. At 50 bits per second, it would then take 12 seconds to transmit a new moving waypoint. This may be acceptable for the purpose of describing a ship trajectory for the accuracy specified for the Shipboard TACAN replacement. If not, the data rate could be increased at the price of modifying receiver software to handle the new data rate. Another alternative is to provide incremental updates to the moving waypoint, which would drastically reduce the number of bits from that of the I-4 message, which is made up of mostly redundant information required for an updated waypoint.

The format, on the other hand, should be close to the format of the GPS satellite data, especially with respect to the length of the subframes and parity algorithms. One exception might be the use of spare spaces in the TLM and HOW words.

V.6 The PL as an LPI Data Link The requirement to use a low-probability-of-intercept data link for the DGPS data transmissions is expressed for the Shipboard TACAN Replacement in Section 2.1 of this report. The requirement states as follows:

> "Transmitter operation should be variable from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height with fixed, rotational, random, raster or jitter illumination to enhance LPI qualities."

---

[15] Computer Program Development Specification for the Receiver Pre-Processor CPCI of the User Segment User Equipment NAVSTAR Global Positioning System, Specification Number CP-RPP-2516. Code Identification 13499, 31 July 1981.

Jeffrey C. Rambo, "Receiver Processing Software Design of the Rockwell International DoD Standard GPS Receiver", Proceedings of ION GPS-89, The Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, CO, September 27-29, 1989.

The PL does provide these capabilities to a degree. The signal structure described above is a spread spectrum signal with a 20.46 MHz bandwidth. Although the pulse transmission power is relatively high, the proposed width of the pulses is narrow, the duty cycle is low and the time of the pulses will be random. Because of these properties, they cannot be predicted by an unfriendly force, especially if their timing is tied to the state of an encrypted P code. This is what would be considered as "random illumination". Thus, the "listener" would have no choice but to detect average power being transmitted. One problem here, however, that without significant hardware modifications to the MAGR, it also only detects average power being transmitted. Thus, from an LPI standpoint, we can not take advantage of the randomization of pulses when considering ratios of detection between the user and the radiometric interceptor.

A "spotlighting" capability could be added. The enhancements realized by using a steerable beam phased-array antenna are obvious. If one were to increase the gain of the transmitting antenna by 20 dB in the desired direction over that of the other directions, the probability of intercept sphere radius would be reduced by a factor of 10 in the other directions.

The techniques described in Appendix II were applied to this proposed PL signal structure. Probabilities of detection were computed for both the MAGR and the interceptor. These probabilities are shown versus distance from the PL in Figure V.12. A data modulation rate of 500 Hz was used for the PL to meet data transmission requirements derived in Appendix IV. The parameters for this evaluation are as follows:

1) $N_{oi} = 10 \log_{10} KT + L_i + NF_i = -204 + 5 + 4 = -195$ dBw/Hz (Noise density of interceptor receiver with an antenna pattern loss of 5 dB),

2) $N_{ou} = 10 \log_{10} KT + L_u - NF_u = -204 + 10 + 4 = -190$ dBw/Hz (Noise density of MAGR with an antenna pattern loss of 10 dB),

3) $B_u =$ 500Hz (Acquisition predetection bandwidth of MAGR),

4) $B_i =$ 20.46 MHz (Predetection bandwidth of interceptor receiver),

5) $IL_u = IL_i =$ 2 dB (Implementation Losses)

7) $T_u = \frac{10}{B_u}$ (Post-detection interval of 20 milliseconds in the MAGR),

8) $T_i =$ 1 second (Post-detection interval for interceptor),

9) $f_o =$ 1227.6 MHz,

10) c = 161,875 nm/second (speed of light),

11) $P_{PK} =$ 52.563 watts,

12) $PDC_u =$ 0.00390625 (Effective user pulse duty cycle for the MAGR),

13) $PDC_i =$ 0.00390625 (Effective interceptor pulse duty cycle).

The probability of false alarm was taken to be 0.001 for the interceptor and 10^{-5} for the MAGR. This is reflected in the resulting decision signal-to-noise ratio.

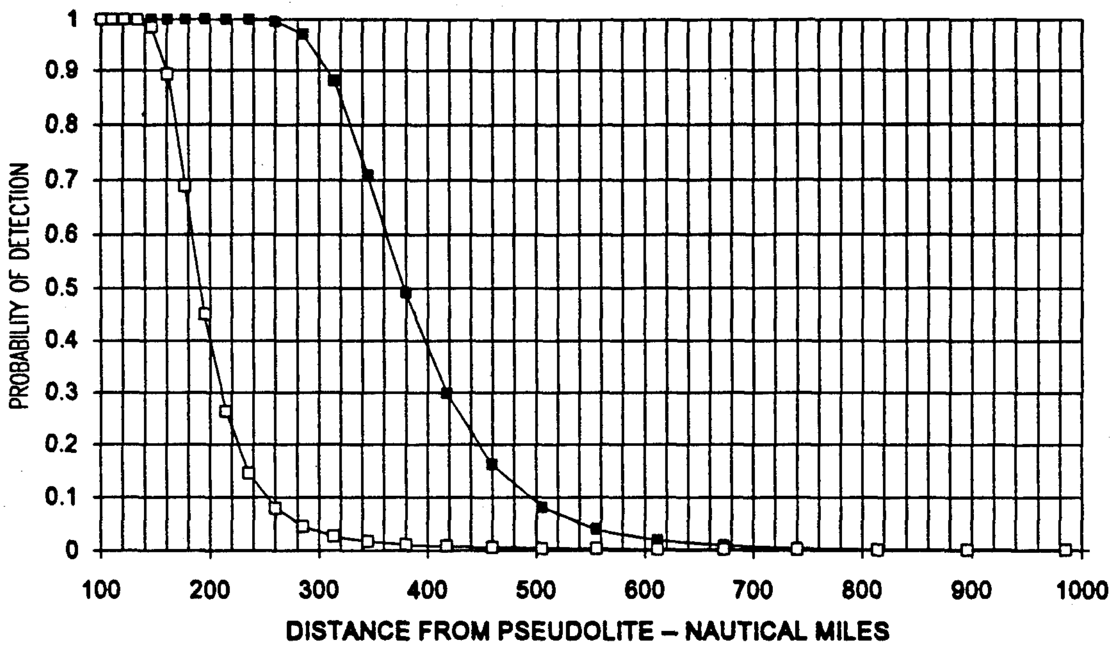

Figure V.12 Detection of PL Probabilities for User and Radiometric Interceptor

Figure V.13 presents the Decision Signal-to-Noise ratio for the same cases evaluated using Equation II.15 of Appendix II. From this figure, we can conclude that ratio for detection probabilities of 0.95 and 0.9 for the MAGR and the interceptor, respectively, to be the following:

1) SNR_{DU} = 16 dB (Required signal-noise ratio for MAGR acquisition),

2) SNR_{Di} = 12.5 dB (Required signal-to-noise for interceptor acquisition).

The required MAGR signal-to-noise ratio SNR_{ur} in the 500 Hz bandwidth for acquisition is 7.3 dB. Then, evaluating the distance ratios using Equation II.19 of Appendix II, we have the ratio $\frac{d_u}{d_i}$ of 1.81. This agrees with Figure V.12. This represents an interceptor detection radius that is 0.55 that of the MAGR, or an area of 0.31.

This is marginal for LPI, and is what one would expect for a continuous direct sequence BPSK signal. In fact, it agrees quite well with that presented in Schoolcraft's paper.[16] It is true that this is a pseudorandom pulsed waveform, but we aren't taking advantage of that in the MAGR, without modifying its signal processing chip to include the appropriate timing circuitry and blanking of noise between pulses. If that were done, the detection radius ratio would improve by the inverse of the fourth root of the duty cycle, which in this case is a factor of four to 7.24 (52.4 times, in terms of area). Now that is significant. That would also improve the performance of the MAGR significantly to where the transmitted PL power could be reduced by a factor of 16, which would also be good. Unfortunately, that modification to the MAGR is probably not worth it, if this is the only use for the PL, especially when a new two way data link could be used for multiple applications.

[16]Ralph Schoolcraft, "Low Probability of Detection Communications, LPD Waveform Design and Detection Techniques," IEEE/DoD MILCOM Proceedings, Reston, VA, 4 - 7 November, 1991.

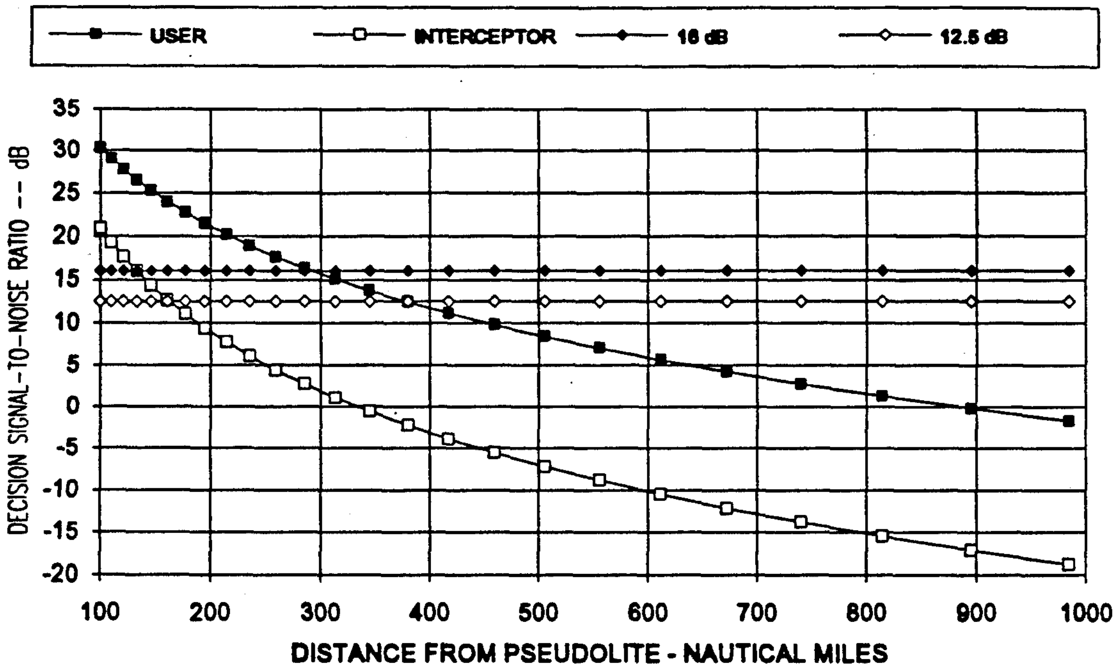

Figure V.13 PL Decision Signal-to-Noise Ratio for User and Radiometric Interceptor

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX VI

GPS SYSTEM SPECIFICATION FOR SHIPBOARD TACAN REPLACEMENT

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

VI.1.0 SCOPE

This specification establishes the system requirements for the various elements required for the Shipboard Tactical Air Navigation (TACAN) Replacement using Differential Global Positioning System (GPS). These elements include the Miniaturized Airborne GPS Receiver (MAGR), the host vehicle mission computer, the data link and shipboard equipment.

VI.2.0 APPLICABLE DOCUMENTS

VI.2.1 Government Documents The following government documents shown form part of this specification to the extent specified herein. In the event of a conflict between documents referenced herein and the contents of this specification, this specification shall be considered a superseding requirement.

SPECIFICATIONS

Federal	(None)
Military	(None)

Other Government Activity

CI-MAGR-300 30 March 1990	Specification for NAVSTAR Global Positioning System (GPS) Miniaturized Airborne GPS Receiver (MAGR) Final Draft
CI-RCVR-3011A 21 March 1988	Prime Item Development Specification for the R-2331/URN Radio Receiver for the User System Segment Navstar Global Positioning System
CI-AE-3061A 21 March 1988	Prime Item Development Specification for the AM-7134/URN Antenna Electronics Amplifier of the User Segment NAVSTAR Global Positioning System
CI-FPRA-3070A 11 November 1987	Critical Item Development Specification for the AS-3822/URN Fixed Reception Pattern Antenna 3 FRPA3 of the User Segment NAVSTAR Global Positioning System
ICD-GPS-200B 30 November 1987	Navstar GPS Space Segment/Navigation User Interfaces
ICD-GPS-224 15 December 1988	Selective Availability and Anti-Spoofing Receiver Requirements with Appendix III, Communications Security (SECRET)
ICD-GPS-222 June 1985	Interface Control Document for the NAVSTAR Global Positioning System User Equipment Auxiliary Output Chip (Secret).
ICD-GPS-059 Revision B 14 June 1991	NAVSTAR GPS Phase III Interface Control Document, GPS User Equipment - MIL-STD-1553 Multiplex Bus Interface, IRNs 001, 003 and 004, Draft MAGR Version
ICD-GPS-176 Revision A 30 April 1986	Shipboard External Computer (MIL-STD-1397A) Interface
ICD-GPS-060A 02 June 1986	Precise-Time-and-Time-Interval (PTTI) Interface
ICD-GPS-073 Revision A 31 March 1986	GPS User Equipment -- Digital Flight Instruments (ARINC 429) Interface

STANDARDS

Federal (None)

Military

MIL-STD-1553B 21 September 1978 Through Notice 2 8 September 1986	Digital Time Division Command/Responses Multiplex Data Bus
MIL-STD-1397A 7 January 1983	Input/Output Interfaces, Standard Digital Navy Systems

Other Government Activity (None)

DRAWINGS (None)

OTHER PUBLICATIONS

ICD-DGPS-TBD Date TBD	DGPS System Interfaces

VI.2.2 Non-government Documents The following non-government documents shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein ant the contents of this specification, the contents of this specification shall be considered a superseding requirement.

SPECIFICATIONS

Electronic Industries Association

EIA Standard RS-422-A December 1978	Electrical Characteristics of Balanced Voltage Digital Interface Circuits

STANDARDS (None)

VI.3.0 REQUIREMENTS

VI.3.1 System Definition The Differential GPS (DGPS) System shall be used as a replacement for the Shipboard Tactical Air Navigation (TACAN). The DGPS System shall contain the Miniaturized Airborne GPS Receiver (MAGR), the Host Vehicle (HV) Mission Computer (MC), the Airborne Low Probability of Intercept Data Link Terminal (ALPIDLT), the shipboard GPS Receiver RCVR 3S, the Shipboard External Computer (SEC), the Shipboard NTDS Controller (SNTDS), the Shipboard Area Navigation (RNAV) Controller (RNAVC), the Shipboard Low Probability of Intercept Data Link Terminal (SLPIDLT) and the Shipboard Data Link Receiver (SDLR). The DGPS System shall provide RNAV information to the MAGR so that it may derive flight instrument information to guide the HV to its designated destination. In general, there are multiple ships and multiple HVs in the system. This specification describes the requirements for one pair. Other ships and other HVs are separated from this pair via multiple access techniques, although HVs may perform DGPS operations between each other with this DGPS System.

The DGPS System shall contain all the elements specified herein.

VI.3.1.1 System Diagram Figure VI.1 presents the functional relationships between the elements of the DGPS System.

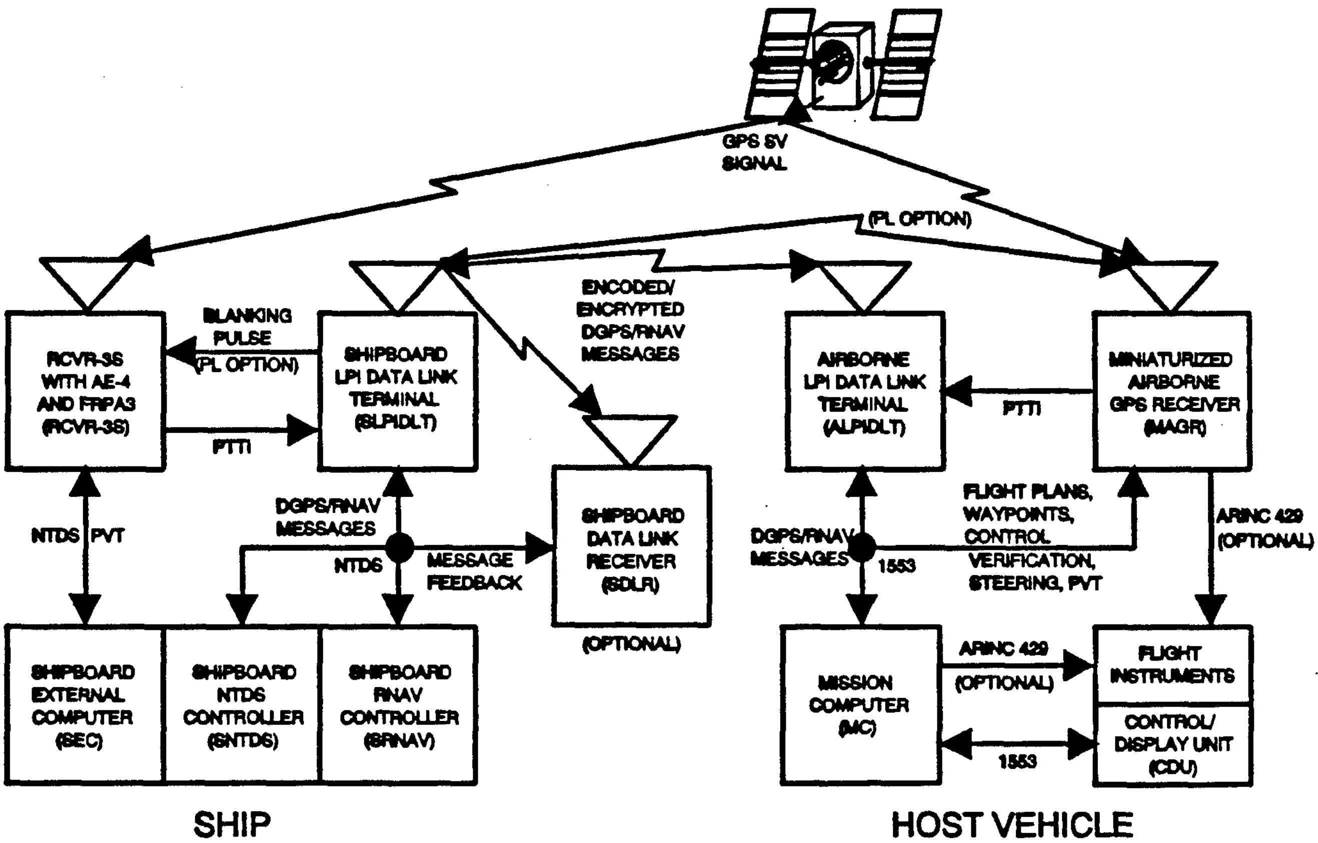

Figure VI.1. DGPS System Functional Block Diagram

VI.3.1.1.1 Miniaturized Airborne GPS Receiver The MAGR's functional capability and performance are as specified in CI-MAGR-300, including the RNAV requirements specified in 40.2 of that specification. The MAGR interfaces to the HV MC via the MIL standard 1553 bus as specified in MAGR version of ICD-GPS-059. The MAGR computes RNAV information for display to the pilot of the HV and outputs that data to the MC for output to the HV flight instruments. On certain HVs, the MAGR outputs the RNAV information directly to the HV flight instruments. The MAGR computes this RNAV information based on flight plans, waypoints and course information provided via that 1553 bus. The MAGR also outputs verification messages verifying the receipt of this data. If the data link is a

GPS pseudolite (PL), MAGR provides for the message reception independent of the 1553 bus and the MC. The MAGR also provides a timing pulse to the ALPIDLT for data link network timing.

VI.3.1.1.2 Host Vehicle Mission Computer The HV MC controls the HV 1553 bus to interface between the MAGR, the CDU, the flight instruments and the ALPIDLT. It establishes protocol with each of these elements and formats and decodes messages to and from the MAGR and the ALPIDLT. It also controls the waypoint and flight plan data bases in the MAGR via the 1553 bus.

VI.3.1.1.3 Airborne Low Probability of Intercept Data Link Terminal The ALPIDLT provides one or two-way communications between the ships RNAV controller and the HV MC, depending upon the data link implementation option. If a PL is used for the data link, the ALPIDLT does not exist. If a two-way communications system is implemented, the system may also be used for determining range and bearing between HVs and for rendezvous operations.

VI.3.1.1.4 GPS Receiver RCVR 3S The RCVR 3S includes the AE-4 Antenna Electronics and a FRPA3 antenna. It provides the reference GPS position and velocity solution of the ship to be used by the RNAV Controller for computing waypoints and flight plans via the SEC. It also provides a timing pulse (PTTI) to the SLPIDLT for data link network timing. If a PL is used for the data link, the RCVR 3S accepts a blanking pulse from the PL.

VI.3.1.1.5 Shipboard External Computer The SEC provides an interface between the RCVR 3S and the NTDS Controller.

VI.3.1.1.6 Shipboard NTDS Controller If a one-way data link is used, the SNTDS computes the RNAV data to be communicated to the HV, formats it for the SLPIDLT, controls the SLPIDLT and receives verification of proper transmission via the SDLR

VI.3.1.1.7 Shipboard RNAV Controller If a two-way data link is used, the RNAVC shares the control of RNAV with the NTDS Controller to compute the RNAV information communicated to the HV, format it for the SLPIDLT, control the SLPIDLT, receive and decode messages from the HV via the SLPIDLT and, optionally, receive verification of proper transmission via the SDLR.

VI.3.1.1.8 Shipboard Low Probability of Intercept Data Link Terminal The SLPIDLT provides one or two-way communications between the ship's NTDS Controller or RNAVC and the HV MC, depending upon the data link implementation option.

VI.3.1.1.9 Shipboard Data Link Receiver The SDLR receives one-way communications messages from the SLPIDLT and passes them to the NTDS Controller for verification of proper transmission. Receipt of two-way communications messages is optional.

VI.3.1.2 Interface Definition

VI.3.1.2.1 Functional Interfaces The functional interfaces of the DGPS System are illustrated in Figure 1. These interfaces are as follows:

a. MAGR/MC Interfaces The MAGR/MC interfaces shall be via the MIL-STD-1553 Multiplex Bus specified in ICD-GPS-059. This interface shall be used by the MC to control the MAGR RNAV data base and RNAV function. In return the MAGR shall use this interface to provide the MC with RNAV data base verification, RNAV status, RNAV steering information and position and velocity reports.

b. MAGR/Flight Instruments On some HVs, the MAGR shall provide steering information to the HV flight instruments as specified in ICD-GPS-073.

c. MAGR/PL If a PL is used as the one-way data link, the MAGR shall receive PL signals to retrieve DGPS information. This interface is specified in ICD-DGPS-TBD.

d. MAGR/ALPIDLT The MAGR shall provide timing information to the ALPIDLT via the PTTI interface specified in ICD-GPS-060 and ICD-GPS-059.

e. MC/ALPIDLT The MC shall control the ALPIDLT, receive DGPS/RNAV messages from the ALPIDLT and provide verification and position reporting messages to the ALPIDLT. This interface shall be via the 1553 bus as specified in ICD-DGPS-TBD.

f. MC/Flight Instruments/CDU The MC shall control the HV flight instruments and CDU.

g. ALPIDLT/SLPIDLT The ALPIDLT/SLPIDLT is a data link system. This interface shall be internal to that system.

h. RCVR 3S/SEC The RCVR 3S shall provide position, velocity and time information to the SEC via the MIL-STD-1397A NTDS bus as specified in ICD-GPS-176.

i. RCVR 3S/SLPIDLT The RCVR 3S shall provide timing information to the SLPIDLT via the PTTI interface specified in ICD-GPS-060 and ICD-GPS-176.

j. RCVR 3S/PL If a PL is used as the one-way data link, the RCVR 3S shall receive a blanking pulse from the PL. This interface is specified in ICD-DGPS-TBD.

k. SEC/SNTDS/RNAVC The SEC shall interface with the NTDS Controller and RNAV Controller and the NTDS Controller shall interface with the RNAV Controller as specified in MIL-STD-1397A, depending upon shipboard implementation option. This interface shall include the data specified in h. and i. above in a format specified in ICD-DGPS-TBD.

l. SNTDS/RNAVC/SLPIDLT The SNTDS or the RNAVC shall provide formatted DGPS/RNAV messages to the SLPIDLT for transmission. If the SLPIDLT is a two-way communication system, the SLPIDLT shall provide formatted DGPS/RNAV return messages from the HV. This interface shall be as specified in ICD-DGPS-TBD.

m. SNTDS/RNAVC/SDLR The SNTDS or the RNAVC shall control the optional SDLR and receive transmission verification messages from the SDLR. This interface shall be as specified in ICD-DGPS-TBD.

n. SLPIDLT/SDLR If the SLPIDLT is a PL, then the SDLR shall be a MAGR and this interface shall be as specified in ICD-DGPS-TBD. If the SLPIDLT is not a PL, the SDLR is a ALPIDLT receiver, and this interface is internal to the data link system.

VI.3.2 Characteristics

VI.3.2.1 MAGR Characteristics The MAGR characteristics shall be as specified in CI-MAGR-300, including Section 40.2, and ICD-GPS-059.

VI.3.2.1.1 Optional MAGR Characteristics If PLs are used as the data link, the MAGR shall meet the following requirements for the PL signal structure specified in Appendix VI.I:

a. The MAGR shall generate coder states for the five P-codes specified as being reserved for Ground Transmitters in ICD-GPS-200B. In addition, based on PL identification (ID), these coder states shall include delays to various times of the week other than the current time of week. The MAGR shall also have the capability of positioning the P-coders to those generated coder states.

b. The MAGR shall have the capability of encrypting the generated P-codes using the Auxiliary Output Chip (AOC).

c. The MAGR shall select a PL code based on a data base containing PL IDs for the various Naval ships as directed by the Operator.

d. The MAGR shall estimate the range to the PL for the purpose of estimating the received code phase for acquisition of the PL signal.

e. The MAGR shall have the capability of acquiring the received PL signal, which will be synchronized to GPS time to within 100 nanoseconds (1 sigma) as transmitted, in a Direct P(Y)-Code Acquisition Mode (State 2 operation). This is known as a "Hot Start" in the MAGR specification. The PLs will only be transmitting the P-code on the L2 frequency.

f. The MAGR shall devote a channel to the PL signal for the purpose of obtaining RNAV information at a rate as high as 500 bits per second synchronized to the GPS one millisecond epochs. (This may require the incorporation of an AOC chip in the existing sixth channel of the current MAGR.)

g. The MAGR shall acquire and track the selected PL signal at a range of 300 nm from the pseudolite at a received $\frac{J}{S}$ level of 41 dB. The transmitted power of the PL will be commensurate with that level.

h. The MAGR shall be capable of decoding the Pseudolite signal data at rates of up to 500 bits per second. The Pseudolite signal may have error detection and correction encoding different than that specified in ICD-GPS-200B.

i. The MAGR shall utilize the Precise Positioning System-Security Module (PPS-SM) for decryption of the received PL data.

j. The MAGR shall be capable of processing the RNAV data collected from the PL signal just as though it was received via the 1553 data bus, but with a different data format.

k. The MAGR shall autonomously assign waypoint numbers to those waypoints received on the PL signals.

VI.3.2.2 Host Vehicle Mission Computer Characteristics The HV MC shall provide the interfaces:

a. Between the MAGR and the ALPIDLT providing RNAV information,

b. Between the MAGR and the Control and Display Unit (CDU),

c. Between the MAGR and the Flight Instruments (on certain HVs).

Requirements b. and c. are standard MC requirements specified elsewhere. The MC interface between the MAGR and the ALPIDLT includes the following functions:

a. Control the 1553 bus. This requirement is a subset of current HV integration requirement. However, this control function shall be augmented to include the ALPIDLT messages. This function is not applicable if the data link is a PL.

b. When ALPIDLT receives a message, establish of a protocol with the ALPIDLT via the 1553 bus.

c. Provide modes for determining range and bearing to other HVs and to perform a rendezvous with other HVs.

d. Receive messages from the data link. These messages contain a subset of the data of ICD-GPS-059 input messages I-3 (Destination Designation), I-4 (Waypoint Definition) and I-25 (Flight Plan Definition) dealing with basic waypoints, waypoint numbers, flight plans and RNAV automatic sequencing of waypoints. They do not contain the data dealing only with the manual mode of RNAV processing. Details of these messages are specified in ICD-GPS-059. Received messages also contained position velocity reporting messages from other HVs. All of the messages may contain parity.

e. Checking parity of the received messages and taking appropriate action based on that check.

f. Decode the header information of the received messages to determine its content.

g. Based on the content received, construct the appropriate 1553 bus message for the MAGR. The format of these messages shall be that of either the I-3, I-4 or I-25 input messages specified in ICD-GPS-059. This construction includes the generation of appropriate mode bits and filling in data not received from the ALPIDLT that is not applicable to the automatic sequencing of waypoints. In the case of position and velocity reporting messages received from other HVs, and that mode of operation has been selected, the MC shall construct I-3, I-4 and I-25 input messages based on those positions and velocities for the purpose of determining range and bearing to anther HV, or to perform a rendezvous with another HV.

h. Establish a protocol with the MAGR. This protocol is as specified in ICD-GPS-059, but also includes the control of the MAGR's Basic Waypoint and Flight Plan data bases. Waypoint numbers must be assigned.

i. Communicate the reconstructed messages to the MAGR via the 1553 bus,

j. Accept response messages from MAGR via the 1553 bus. These messages are the G-3, G-4, G-25 and G-26 output messages specified in ICD-GPS-059. The G-3 output message shall be used by the MC for its internal flight instrument and CDU functions. Data from the G-4, G-25 and G-26 output messages shall be also used for those functions. In addition, selected data from those messages shall be formatted into a verification message to the ALPIDLT for transmission to the RNAV Controller via the SLPIDLT, if a two-way data link is implemented.

k. Set the navigation mode of the MAGR and select the G-9 GPS Background Navigation Data output message to be used for position reporting via the I-1 GPS Control input message as specified in ICD-GPS-059.

l. Receive additional messages from the MAGR via the 1553 bus. These include the G-9 and G-20 (PTTI) output messages specified in ICD-GPS-059. The PTTI output shall be formatted into a message for the ALPIDLT for its time synchronization function. The G-9 output message shall be formatted into a position and velocity reporting message to the ALPIDLT for transmission to the RNAV Controller via the SLPIDLT, if a two-way data link is implemented.

m. Strip data out of the messages not pertinent to RNAV and air traffic control.

n. Add headers and parity and format messages for output to ALPIDLT.

o. Establish protocol with the ALPIDLT and command transmission of messages.

VI.3.2.3 Airborne Low Probability of Intercept Data Link Terminal Characteristics If a PL is not used as the data link, an ALPIDLT shall be developed that has the performance obtainable from the following characteristics. Parameters may vary except for those that establish compatibility with other data links. In the case that it is only a one-way data link, only the receive functions apply.

a. Frequency Band The ALPIDLT shall be the airborne version of a terminal for an LPI/Anti-Jam (AJ) secure data link that operates either in the LINK-4A frequency band (225-400 MHz) or in the JTIDS/TACAN frequency band (960-1215 MHz, less IFF frequencies). If it operates in the LINK-4A band, it shall also include a backward compatible FSK LINK-4 and FSK LINK-4A modes.

b. LPI Definition The probability of detection of transmissions from the ALPIDLT by a radiometric interceptor shall be less than 20% of the communications range, where the interceptor has a probability of detection of 0.9 with a false alarm rate of 0.001.

c. Legacy The development of the ALPIDLT shall benefit from an evolution of JTIDS technology programs extrapolated in a reduced cost, performance improvement manner.

d. Characteristics

aa. Time division multiplex Time slots at the rate of 125 slots per second shall be provided. The duration of each time slot is equal to 8 milliseconds to be compatible with LINK-4 timing.

bb. Message duration Messages may vary over multiple time slots.

cc. Waveform The waveform shall be a hybrid frequency hopping direct sequence PN time hopping type for LPI optimization and multiple access.

dd. Symbols A five bit symbol shall be encoded into a 32 chip PN sequence. The PN sequence shall be at a 1 MHz bit rate for a pulse duration of 32 μs.

ee. Time hopping A minimum of 32 μs shall be provided between time hops pulses in a encrypted pseudorandom time hopping protocol.

ff. Time slots There shall be 125 symbol periods in a time slot. Messages may extend over multiple time slots.

gg. Symbol coding 32'ary cyclic shift coding shall be used. In addition, Reed-Solomon encoding of the symbols shall be used to achieve an error free message rate more than 99% of the time on a 75 bit message.

hh. Frequency hopping rate The frequency hopping rate shall the reciprocal of the minimum symbol period duration of 64 μs for one 32 μs pulse-on period and one 32 μs pulse-off period. The frequency hopping rate shall be 15,625 hops per second.

ii. Frequency hop bandwidth The granularity of a frequency hop shall be $\frac{3}{5}$ of the chipping rate. The number of hop bins shall be the total data link bandwidth in Hz x $\frac{5}{3}$ x 10^{-6}.

jj. Modulation Minimum Shift Keying (MSK) shall be implemented to minimize the required bandwidth for each frequency hop bin.

kk. Transmitter power The peak power of the transmitted pulse shall be equal to 15 watts at L-Band or 1.5 watts in the LINK-4A band to achieve a 300 nm communication range. Transmitted power shall be adjustable to vary the communication range as well as the intercept range.

ll. Receiver noise figure The receiver noise figure shall be less than or equal to 3 dB, including cable losses.

mm. Receiver sensitivity The receiver sensitivity shall be better than -114 dBm. The message error rate at this level without jamming shall be less than 1%.

nn. Synchronization preamble The synchronization preamble shall be made up of three random time hopped symbols preceding the message. The probability of synchronization at the sensitivity point shall be greater than 0.995 at a false alarm rate less than 1 x 10^{-6}.

oo. Interleaving Symbols shall be interleaved to improve performance jamming and signal fading.

pp. Cryptovariables Accept encryption cryptovariables from an external device such as a KYK-13.

qq. Encryption Encryption shall utilize the project Thornton chip embedded in the signal processor. All aspects of the waveform shall be encrypted.

rr. Data rate The uncoded data rate shall be compatible with LINK-4A. The ALPIDLT shall have the capability of reducing that rate for improved LPI by deleting symbols from the transmission of time slots.

ss. LINK-4 backward compatibility The ALPIDLT shall also provide FSK modulation/demodulation if operating in the LINK-4 band. The data link shall also be capable of accepting and demodulating instantaneous data rates of 10 kbps requiring peak frequency deviations of 10 kHz.

tt. Physical characteristics The ALPIDLT shall be the size of a $\frac{1}{4}$ ATR line replaceable unit.

uu. Power dissipation The ALPIDLT shall dissipate less than 200 watts if operating at L-Band and less than 50 watts if operating in the LINK-4A frequency band.

vv. EMI Operation of the ALPIDLT shall not degrade the performance of other platforms or force systems.

ww. Number of users An unlimited number of units shall be able to use the system. Unlimited here means more that the number of ships in the Navy's fleet plus the number of aircraft in the Navy's inventory.

VI.3.2.4 Shipboard Equipment Characteristics The shipboard equipment requirements for each of three DGPS System options are described below. In each case a representative implementation is given. These given implementations are for illustration of the requirements only. It is assumed in the following discussions that the NTDS Controller or the RNAV Controller will generate and format all messages. The RCVR 3S will only output the necessary data and the Shipboard External Computer will only pass the data on, with the exception that it may smooth the GPS position and velocity against the INS outputs.

VI.3.2.4.1 DGPS System Option 1 -- One-Way Data Link Broadcast Figure VI.2 illustrates a representative shipboard implementation for DGPS System Option 1, using a one-way data link to broadcast DGPS information. The shipboard equipment requirements for DGPS System Option 1 are the following:

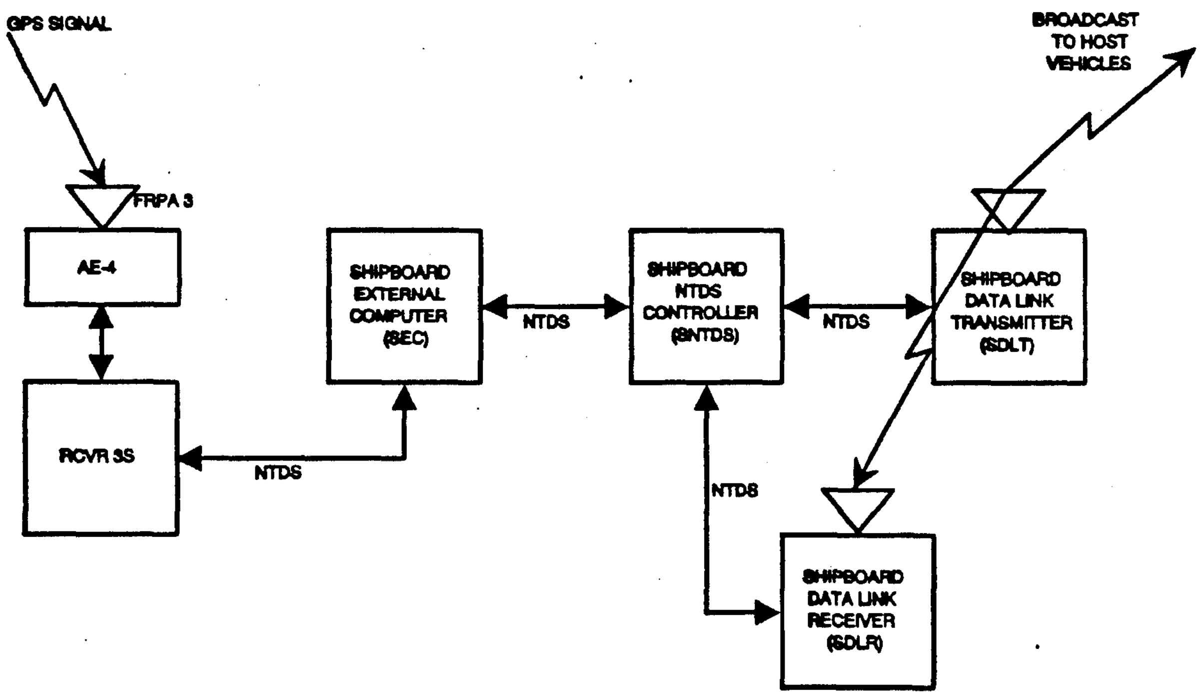

Figure VI.2. Option 1 Shipboard Equipment Configuration

a. RCVR 3S, AE-4 and FRPA 3 Requirements No additional requirements are imposed on the RCVR 3S, the AE-4 and the FRPA 3 to implement DGPS System Option 1.

b. Shipboard External Computer Requirements The SEC shall pass along to the NTDS controller the RCVR 3S GPS navigation solution (position and velocity), either in its raw form or smoothed against INS outputs.

c. Shipboard NTDS Controller Requirements The SNTDS shall accept the GPS navigation solution (positions and velocity) outputs from the SEC. The SNTDS shall use these navigation solutions to perform the following functions:

1) Generate moving waypoints of the ship's trajectory consistent with the I-4 Waypoint Definition 1553 bus message for the MAGR.

2) Format and output these messages at a determined rate to the Shipboard Data Link Transmitter (SDLT). See 5) below.

3) Control the transmissions of the SDLT.

4) Buffer these messages and compare them to those received from the Shipboard Data Link Receiver (SDLR). If an error is detected (non-comparison), terminate the transmission of the SDLT until the problem is resolved.

5) Propagate the moving waypoint received from the SDLR to current time. Compare the propagated position with the GPS navigation solution received from the SEC. If the propagated position differs from the navigation solution by a predetermined amount, generate and format a new message.

6) Control the reception of the SDLR and accept received messages and reception status from the SDLR.

7) Verity the current LPI and AJ capabilities of the SDLT based on the reception status received from the SDLR.

d. Shipboard Data Link Transmitter Requirements The SDLT shall accept formatted messages from the SNTDS Controller. The SDLT shall meet the requirements specified in Paragraph VI.3.2.3 above for the transmitter portion of the ALPIDLT with the following exceptions:

1) The SDLT does not have to meet the ALPIDLT size and power requirements.

2) The SDLT shall have additional power transmission capability to overcome antenna cable losses.

3) Variable transmitter operation shall be used to cover from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height to enhance LPI qualities.

e. Shipboard Data Link Receiver Requirements The SDLR shall be separated from the SDLT so as to receive messages transmitted by the SDLT via its antenna for signal transmission verification. The SDLR shall perform the functions of the receiver portion of the ALPIDLT specified above in Paragraph VI.3.1.1.2, with the following exceptions:

1) Measure the signal power levels to verify the LPI and AJ capabilities of the transmissions.

2) Generate signal reception status information that includes the received signal power levels.

3) Output the message and status data to the SNTDS.

VI.3.2.4.2 DGPS System Option 2 -- Two-Way Communication Data Link Figure VI.3 illustrates a representative shipboard implementation for DGPS System Option 2 using a two-way communication data link to broadcast and receive DGPS and RNAV information. The shipboard equipment requirements for DGPS System Option 2 are the following:

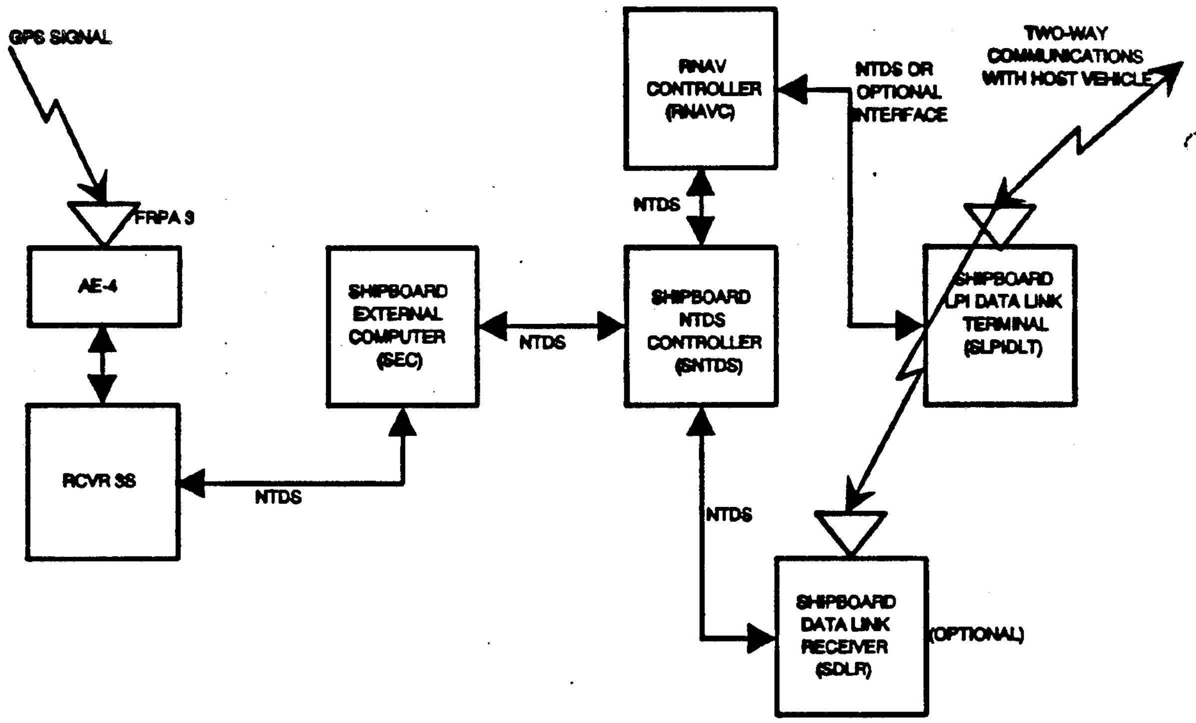

Figure VI.3. Option 2 Shipboard Equipment Configuration

a. RCVR 3S, AE-4 and FRPA 3 Requirements No additional requirements are imposed on the RCVR 3S, the AE-4 and the FRPA 3 to implement DGPS System Option 2.

b. Shipboard External Computer Requirements The SEC shall pass along to the SNTDS the RCVR 3S GPS navigation solution (position and velocity), either in its raw form or smoothed against INS outputs.

c. Combined Shipboard NTDS Controller and RNAV Controller Requirements The distinction between the requirements for the SNTDS and the RNAVC is not specified. The SNTDS and RNAVC shall accept the GPS navigation solution (positions and velocity) outputs from the SEC. The SNTDS and RNAVC shall use these navigation solutions to perform the following functions:

1) Generate moving waypoints of the ship's trajectory consistent with the I-4 Waypoint Definition 1553 bus message for the MAGR.

2) Generate RNAV messages consistent with the I-3 Destination Designation and I-25 Flight Plan 1553 bus messages for the MAGR.

3) Format and output these messages at a rate consistent with RNAV requirements to the SLPIDLT.

4) Control the transmissions of the SLPIDLT.

5) Accept messages received by the SLPIDLT from the HV.

6) Buffer the transmitted messages and compare them to those received by the SLPIDLT. If the information received from the HV derived from the MAGR's G-3 Destination Data, G-4 Waypoint Data and G-25 Flight Plan/Profile Data messages, alert the RNAV function of the discrepancy.

7) Pass messages received by the SLPIDLT from the HV derived from the MAGR's G-9 Background Navigation Data output message to the RNAV function for HV position and velocity reporting and HV position tracking.

d. Shipboard NTDS Controller and RNAV Controller Optional Requirements As an option, the SNTDS and RNAVC shall control an optional SDLR and accept messages and reception status from that SDLR and perform the following:

1) Buffer the messages formatted for the SLPIDLT and compare them to those received from the SDLR. If an error is detected (non-comparison), terminate the transmission of the SLPIDLT until the problem is resolved.

2) Propagate the moving waypoint received from the SDLR to current time. Compare the propagated position with the GPS navigation solution received from the SEC. If the propagated position differs from the navigation solution by a predetermined amount, generate and format a new message.

3) Verity the current LPI and AJ capabilities of the SLPIDLT based on the reception status received from the SDLR.

e. Shipboard LPI Data Link Terminal Requirements The SLPIDLT shall accept formatted messages from the SNTDS and RNAVC. The SLPIDLT shall meet the requirements specified in Paragraph VI.3.2.3 above for the ALPIDLT with the following exceptions:

1) The SLPIDLT does not have to meet the ALPIDLT size and power requirements.

2) The SLPIDLT shall have additional power transmission capability to overcome antenna cable losses.

3) Variable transmitter operation shall be used to cover from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height to enhance LPI qualities.

4) Receive signals transmitted by the HV ALPIDLTs.

5) Decode the received signals and collect the message data modulated on the signals.

6) Measure the signal power levels to verify the LPI and AJ capabilities of the transmissions of the HV ALPIDLTs.

7) Generate signal reception status information that includes the received signal power levels and output that data to the SNTDS and RNAVC.

ff. Optional Shipboard Data Link Receiver Requirements The optional SDLR shall be separated from the SLPIDLT so as to receive messages transmitted by the SLPIDLT via its antenna for signal transmission verification. The SDLR shall perform the functions of the receiver portion of the ALPIDLT specified above in Paragraph VI.3.1.1.2, with the following exceptions:

1) Measure the signal power levels to verify the LPI and AJ capabilities of the transmissions.

2) Generate signal reception status information that includes the received signal power levels.

3) Output the message and status data to the SNTDS and RNAVC.

VI.3.2.4.3 DGPS System Option 3 -- Pseudolite Broadcast Figure VI.4 illustrates a representative shipboard implementation for DGPS System Option 3, using a pseudolite to broadcast DGPS information. The shipboard equipment requirements for DGPS System Option 3 are the following:

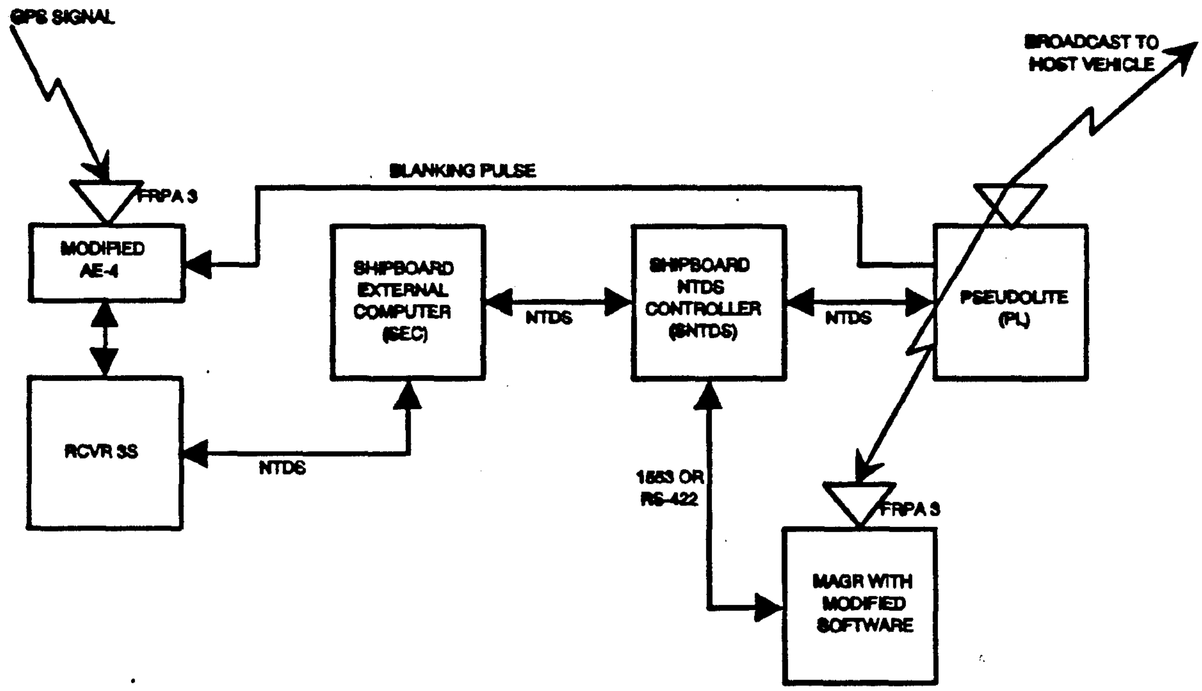

Figure VI.4. Option 3 Shipboard Equipment Configuration

a. RCVR 3S, AE-4 and FRPA 3 Requirements The AE-4 shall accept a blanking pulse from the PL and blank out signal reception for the duration of the blanking pulse. The start and stop recovery time shall be sufficiently small so as to not affect the performance of the RCVR 3S signal tracking capability.

b. Shipboard External Computer Requirements The SEC shall pass along to the NTDS controller the RCVR 3S GPS navigation solution (position and velocity), either in its raw form or smoothed against INS outputs.

c. Shipboard NTDS Controller Requirements The SNTDS Controller shall accept the GPS navigation solution (positions and velocity) outputs from the SEC. The SNTDS Controller shall use these navigation solutions to perform the following functions:

1) Generate moving waypoints of the ship's trajectory consistent with the I-4 Waypoint Definition 1553 bus message for the MAGR.

2) Format and output these messages at a determined rate to the PL. See 5) below.

3) Control the transmissions of the PL.

4) Buffer these messages and compare them to those received from the MAGR. If an error is detected (non-comparison), terminate the transmission of the PL until the problem is resolved.

5) Propagate the moving waypoint received from the PL to current time. Compare the propagated position with the GPS navigation solution received from the SEC. If the propagated position differs from the navigation solution by a predetermined amount, generate and format a new message.

6) Control the reception of the MAGR and accept received messages and reception status from the MAGR via either a 1553 or RS-422 data bus.

7) Verity the current LPI and AJ capabilities of the PL based on the reception status received from the MAGR.

d. Pseudolite Requirements The PL shall accept formatted messages from the SNTDS. The PL shall perform the following functions:

1) Low Probability of Intercept (LPI) Electromagnetic emissions shall be minimized to present an LPI capability. Variable transmitter operation shall be used to cover from a maximum hemispherical distance of at least 300 nm to graduated range reductions with a "spotlight" aim capability in azimuth, elevation, base height and ceiling height to enhance LPI qualities. The probability of detection of transmissions from the PL by a radiometric interceptor shall be less than 60% of the communications range, where the interceptor has a probability of detection of 0.9 with a false alarm rate of 0.001.

2) EMI Operation of the PL shall not degrade the performance of other platforms or force systems, including the shipboard and airborne GPS receivers.

3) Signal structure The PL shall have the signal structure specified in Appendix VI.I

4) Number of users: An unlimited number of units shall be able to use the PLs.

5) Cryptovariables Accept encryption cryptovariables from an external device such as a KYK-13.

6) Blanking pulse The PL shall provide a transmitting blanking pulse to the AE-4 antenna electronics.

e. MAGR Requirements The MAGR shall receive messages transmitted by the PL for a signal structure such as derived in Appendix VI.I. The MAGR shall perform the following functions:

1) Decode the received signals and collect the message data modulated on the signals.

2) Measure the signal power levels to verify the LPI and AJ capabilities of the transmissions.

3) Generate signal reception status information that includes the received signal power levels.

4) Output the message and status data to the SNTDS Controller.

APPENDIX VI.I

DGPS SYSTEM PSEUDOLITE SIGNAL STRUCTURE SPECIFICATION

VI.10.0 PSEUDOLITE SIGNAL STRUCTURE

The following parameters specify the PL signal structure for the DGPS System:

a. P code PRN number,

b. Pulse duty cycle (PDC),

c. Pulse repetition frequency (PRF) and pulse width (PW),

d. Frequency and frequency offset,

e. Transmitted power,

f. Pulse pattern (i.e. time position of pulses),

g. Signal encryption,

h. Data and message structure.

These parameters are defined herein. Some of the parameters are highly related and are defined together.

VI.10.1 P Code PRN Number ICD-GPS-200B defines five PRN numbers, 33 through 37, as being reserved for uses other than satellites (e.g. ground transmitters). These PRN numbers shall be used for the PLs in the DGPS System. Although there are not enough of them, many PRN numbers can be derived from those five by slicing them up in time. These five codes shall be split into 840 one hour codes by assigning a PRN code number, plus a time-of-week to each one. So that the codes don't have to be reset at the end of the one hour period, a PL shall be assigned a code plus a delay. That is, PL #1 shall be assigned the code 33 with no delay, PL #2 shall be assigned code 33 with a one hour delay, ... PL #168 shall be assigned code 33 with a 167 hour delay, PL #169 shall be assigned code 34 with no delay, etc, up to PL #840 shall be assigned code 37 with a 167 hour delay. Thus, the codes will only have to be reset at their natural end-of-week, which is not necessarily the end of the GPS week. They will just simply be initialized with a different time.

VI.10.2 Pulse Duty Cycle Pulse duty cycle shall be defined with respect to the pulse repetition frequency (PRF) and the pulse width (PW) as

$$PDC = PRF \times PW \tag{VI.10.1}$$

For example, a PRF of 1000 pulses per second and a PW of 1 microsecond results in a PDC of 0.001.

VI.10.3 Pulse Repetition Frequency and Pulse Width Given the PDC, these two parameters shall be defined together. The PW shall be an integer number of P chips in time as shall be the time between pulses that defines the PRF. PW shall be 100 P chips (9.7752 microseconds, which is 10 C/A code chips), and the average PRF shall be 399.60937 pulses per second (one pulse every 25600 P chips, or 256 pulse periods, on the average), resulting in a PDC of exactly 0.00390625 $\left[\frac{1}{256}\right]$.

VI.10.4 Frequency and Frequency Offset The PL signal shall be transmitted near the GPS L2 signal frequency as specified in ICD-GPS-200B at 1227.6 MHz. The PL frequency shall be offset from that frequency by 60-70 kHz to reduce the cross correlation interference with satellite signals.

VI.10.5 Transmitted Power The average transmitted power (P_T) of an L2 frequency PL for an average received power (P_r), through a receiving antenna with gain G_a, at a distance (d) in nm is

$$P_T = P_r + 20\log_{10}\left[\frac{4\pi d}{\lambda}\right] - G_a = P_r + 20\log_{10}d + 99.582 - G_a \text{ dBw} \qquad \text{(VI.10.12)}$$

where the L2 signal wavelength $\lambda \left[\frac{c}{f_0}\right]$ is 0.000131863 nm. Thus, for a distance of 300 nm and a average received power of to match the received L2 signal power of -166 dBw from a GPS satellite, the average transmitted power is -6.876 dBw, or 205.33 milliwatts. This includes an antenna gain of -10 dB.

The peak power (P_{PK}), given a PDC, is

$$P_{PK} = P_T - 10\log_{10}\text{PDC dBw} \qquad \text{(V.13)}$$

Thus, for the PDC of 0.00390625, the peak power shall be 17.21 dBw, or 52.563 watts.

VI.10.6 Pulse Pattern The PRF of the transmission shall not be constant to prevent the pulses from being received synchronous with navigation data bit edge timing received from a satellite. The pulses shall also be distributed uniformly with time over some time interval smaller than a bit period with the average PRF of one pulse every 256 pulse periods as specified above and for the PW defined above of 100 P chips. This results in an average of 7.9921875 pulses per data bit period.

The pulse pattern shall also be pseudorandom to maximize LPI. Thus, the pulse pattern shall be tied to state of the P code as follows: Latch the first eight code chips (bits) of a 100 chip pulse, and use the eight bits to determine in which of the following 256 pulse period window the next pulse shall be transmitted. Thus, the time between the leading edge of pulses will vary from 1 to 511 pulse periods, with an average of 256 pulse periods, since the average pulse position in each interval is position 128.

This pattern also allows more than one PL to operate in the same region with minimal interference between them. This is because the probability of pulses from more than one PL being received at the same time is very small, no matter what the relative geometry of the PLs is. Thus, if an airborne GPS receiver were to operate very close to one of the PLs that is suppressing its signal input during its reception, that receiver can still receive the other PL(s). very few of the other PL(s)' pulses will be blanked out by a strong pulse from the nearby PL.

VI.10.7 Signal Encryption The P code transmitted by the PL in the same way the GPS satellite P codes are encrypted, providing a Y code transmission. Also, the GPS Navigation Data encryption algorithms to encrypt the DGPS data.

VI.10.8 PL Data Structure and Format The data modulated onto the PL P(Y) code shall provide the airborne GPS receiver with DGPS information. This data shall be modulated at a rate of 500 bps to provide sufficient data capacity for the DGPS System. Except for this data rate, the data format shall use the 30 bit words and (32,26) Hamming parity in 10 word subframes, which is exactly the same format transmitted from the GPS satellites as specified in ICD-GPS-200B. However, because of the higher data rate, every 100th word shall be a TLM word with a synchronization preamble, followed by a HOW with the truncated Z-Count, which will occur every 6 seconds.

THIS PAGE INTENTIONALLY LEFT BLANK